



Eco-innovation dynamics and sustainability – new perspectives in innovation studies illuminated through the case of lighting and its energy consumption

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Title

Eco-innovation dynamics and sustainability - new
perspectives in innovation studies illuminated
through the case of lighting and its energy
consumption

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Abstract

There is an increasing consensus about the need to reduce the environmental burden of economic activities. The concept of sustainable development has led to increased efficiency of the economic process through innovation, which is now the main strategy applied both to preserve environmental capital and to achieve economic growth. Consequently, many innovations have been given the label of “eco” due to their ability to improve the efficiency of the economic process.

The history of energy consumption is a paradigmatic example of diffusion of this type of eco-innovations. The efficiency of converting energy in lighting has increased a thousand times in the last century, and is expected to increase three to six times in the near future, thanks to the development and diffusion of LED technology. Consequently, many societal actors and policy-makers now rely on this promising eco-innovation to reduce the consumption of energy during the provision of light.

Researchers have already investigated the dynamics of production and consumption associated with the most recent light “revolutions”. Interestingly, these revolutions resulted in increased energy consumption for the provision of light, even if energy efficiency increased. The same paradox has been experienced by other sectors and has been discussed in the eco-innovation literature, with innovation being considered as both a cause of and a solution for environmental degradation.

The present thesis has investigated the roots of this paradox and the implications for policies and societies, of a new conceptualization of eco-innovation that can overcome such paradox. In my view, the paradox stems from two conceptual weaknesses of the traditional eco-innovation literature. First, this literature has underestimated the debate between the advocates of weak sustainability (that is, sustainability as the sum of natural and human-made capitals) and the ones of strong sustainability (that is, sustainability as the preservation of natural capital). Second, the eco-innovation literature has not integrated the findings of the rebound effect literature, in which relations between innovation and consumption have been widely analyzed. As a result, a current popular definition of eco-innovation, implicitly based on the concept of weak sustainability, has been erroneously promoted to achieve specific environmental targets (such as a reduction of energy consumption) that represent the strong sustainable perspective.

For this reason, I propose a new conceptualization of eco-innovation for strong sustainability that focuses specifically on the impacts of any innovation with respect to consumption. Based on this conceptualization, an eco-innovation is not one that increases efficiency, but one that reduces overall environmental impacts.

The dualism of the eco-innovation concept has important consequences for the specificity of the case study, and for the more general discussion about innovation and sustainability. In the case of energy consumption for lighting, the thesis indicates the need to frame future innovations in a context that fosters the emergence of new practices leading to energy saving. One of the several recommendations I make in this thesis is that the future smart light system based on the LED technology should be provided by a new type of lighting service company that aims to sell light saving. In fact, LED is not only a more efficient technology; it is also superior to

other technology in numerous ways. For this reason, the future smart LED light system is expected to encourage demand for lighting, as will the emergence of new lighting players that will generate new market opportunities. The actual impacts of these dynamics, in terms of energy consumption, will depend on which practices will be developed and how these new technological opportunities will be integrated. For that reason, there is a need for a better conceptualization of eco-innovation that can provide a better understanding of the potential opportunities and risks presented by the most promising innovations for sustainability. Similarly, policy makers should seek to deconstruct the current concept of the lighting sector, from being the realm of the electric bulb, to the realm of light and lighting. In fact today many actors which provide (natural) light, as for example windows producers, are not framed as part of the lighting sector. The thesis suggests to policy makers to promote a more functional definition of the boundaries of the lighting sector, including all the players that provide both natural and artificial light.

When I went through Switzerland in a motor-car, so that I could visit little towns and villages, I noted the effect of artificial light on the inhabitants. Where water power and electric light had been developed, everyone seemed normally intelligent. Where these appliances did not exist, and the natives went to bed with the chickens, staying there until daylight, they were far less intelligent."

Thomas Edison

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1 Introduction

Since I started my Ph.D. studies three years ago, I have been greatly interested in the development of new conceptualizations of eco-innovation in the context of innovation studies. This interest arose because the literature on innovation for sustainability indicates that there is a paradox between innovation¹ and environment (Debref, 2012; Fölster and Nyström, 2010; Hekkert *et al.*, 2007). Indeed, innovation has been considered to be both a cause of and a solution for environmental degradation (Porter and Linde, 1995).

Jevons (1865) was the first to highlight the existence of a paradox. As he put it, *“It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth ... [E]very ... improvement of the engine, when effected, does but accelerate anew the consumption of coal”* (as cited in Blake, 2005, p. 12). Nevertheless, the eco-innovation conceptualization did not integrate Jevons’s paradox, and instead focused on comparing the intrinsic environmental performances of any innovation. In fact, Pearson and Kemp (2007) defined eco-innovation as *“the production, assimilation or exploitation of a product, production process, service or management or business method that is novel to the organisation (developing or adopting it) and which results, throughout its life cycle, in a reduction of environmental risk, pollution and other negative impacts of resources use (including energy use) compared to relevant alternatives”* (p. 7; original emphasis). This resulted in the majority of innovations having the label ‘eco,’ simply because they increase the efficiency of the economy. As Pearson and Kemp (2007) indicated, *“It has been estimated ... that the majority of technological innovations probably offer environmental benefits”* (p. 5).

According to Pearson and Kemp, eco-innovation is a pervasive force in the economic process, so the majority of innovations offer environmental benefits. However, few people would argue that environmental sustainability has improved in recent decades (Rockstrom *et al.*, 2009). Such a contradiction represents the essence of the paradox between eco-innovation and sustainability. Hekkert *et al.* (2007) called for the need to shape *“the direction of innovation and technological change”* (p. 413) because of the *“often severe negative side effects”* (p. 414). While Pearson and Kemp indicated that the normal course of innovations is to provide environmental benefits, Hekkert *et al.* indicated that innovations should be guided because they often have negative side effects on the environment. Carrillo *et al.* (2010) attempted to overcome these differences, acknowledging that the eco-innovation definition has several fallacies, dividing eco-innovation into two separate concepts. They distinguished between *“eco-efficiency”* and *“eco-effectiveness,”* whereby the former may be ineffective at improving sustainability because *“its goals, however admirable, are often regarded as insufficient in so far as increases in environmental efficiency tend to be erased by subsequent growth (rebound effect)”* (p. 1076). Eco-effectiveness is the most promising form because it *“goes beyond improvements in existing activities and challenges companies and society at large to redefine their production and behavioral patterns”* (p. 1076).

¹ For the sake of simplicity, I have used the terms “innovation” and “new technologies” interchangeably to mean “innovation and technology change.”

The debate about the paradox indicates a gap in the ability of the current definition of eco-innovation to understand relations between innovation and sustainability. Therefore, as a researcher, I found it relevant to investigate relations between innovation and environment and to provide new knowledge on the topic. Even though this paradox has been known since the 19th century, thanks to the work of Jevons, the birth of the sustainability concept has increased the reliance on solving environmental problems through innovation. This has resulted in an increased popularity of “green” cars, lamps, airplanes, and the like that, if fully developed, are expected to reduce the environmental impacts of anthropogenic activities.

The most important finding of my research is that the unsustainable patterns of some eco-innovations are not the result of a paradox, but of a misunderstanding of the relations between sustainability and eco-innovation. The mainstream definition of eco-innovation does not focus on increasing sustainability, which is understood as the reduction of environmental burden. Consequently, it is expected that some eco-innovations will show unsustainable patterns.

In order to understand the above statement, it is important to study the evolution of the sustainability literature in connection to the eco-innovation one. Throughout this thesis, I argue that sustainability has been mainly framed in terms of weak sustainability. An economy is weakly sustainable when *“the ratio of savings to income (which allows investment) is larger than the sum of the ratios of depreciation of human-made capital and ‘natural capital’”* (Martinez-Alier 1995). The efficient conversion of natural capital into human-made capital is the main criterion with which to evaluate the degree of weak sustainability of any innovation. The eco-innovation literature was highly influenced by the weak approach to sustainability. Pearson and Kemp’s definition of eco-innovation as *“any kind of innovations which has a reduced environmental impacts compared to the relevant alternatives”* (Pearson and Kemp, 2007) shows a clear weak sustainable perspective. That definition assesses the environmental performance of a specific innovation and compares it to relevant alternatives. Therefore, being “eco” is a matter of environmental performances through the innovation’s entire life cycle. A car engine is “eco” if it pollutes less than the other engines available in the market. A light bulb is “eco” if it consumes less energy than the relevant alternatives. Such a concept embeds the notion of efficiency at its very root (Domar, 1961), because it indicates the capacity to transform natural capital (for example, petrol for a car, wattage for a lamp) into human-made capital (mobility for the car and light for the lamp, to follow the same two examples). Therefore, Pearson and Kemp define innovations as “eco” through the lenses of weak sustainability. Instead, the notion of strong sustainability focuses on the preservation of a critical amount of natural capital. In that notion, sustainability relies on the patterns of consumption of natural capital, without considering the dynamics of human-made capital. Therefore, an innovation is “eco” – from a strong sustainable perspective – if it reduces the consumption of natural capital. Relations between weak and strong sustainability have been investigated in the rebound effect literature, and it is known that an increase of efficiency (that is, weak sustainability) does not ensure a reduction in consumption (that is, strong sustainability) (Brookes, 1992; Daniel Khazzoom, 1980; Saunders, 1992). Therefore, it is a conceptual flaw to expect to achieve strong sustainability through eco-innovations based on the weak sustainable principle.

The main conclusion of this thesis is that the conceptualization of eco-innovation must be more consistent with the notion of sustainability that we aim at. If we pursue weak sustainability, Kemp’s definition of eco-

innovation is fine. If we pursue strong sustainability, however, we should change the definition. In this thesis, I propose a definition of eco-innovation for strong sustainability as *“any kind of innovation that diffuses new practices that reduce the environmental impacts of society.”* The proposed definition evaluates whether or not society uses innovations in a way that encourages environmental sustainability. For example a car engine is “eco” if it activates new patterns that result in less consumption of petrol for mobility. Through the thesis, I will explain the implications of these two conceptualizations.

Before continuing, it is important to highlight that a society can survive with both weak and strong perspectives on sustainability. Sometimes, these two perspectives are even used together mixed in the policy discourse. The case of policies for climate changes is paradigmatic. Mitigation policies have set certain targets (for example, reducing greenhouse gas (GHG) emissions by 20 percent) that are examples of strong sustainability, because they aim to conserve a critical amount of natural capital². Adaptation policies are an example of weak sustainable strategies. In fact, societies should try to minimize the adverse effects of climate change and take advantage of *“opportunities that may arise”* (European Commission, 2014). The capacity to exploit opportunities and minimize effects of climate changes depends on the available knowledge, resources, and infrastructures (that is, the human made capital). In that view, weak sustainability indicates that we may end up ruining the climate (that is, lowering natural capital beyond a critical threshold), but human knowledge may be able to cope with that, and even increase overall welfare through the exploitation of potential opportunities. In brief, I argue that the real limitation of the current literature is the inconsistent use of a definition of eco-innovation for weak sustainability in connection to strong sustainability.

Throughout this thesis, I discuss the main implications of the different notions of sustainability and eco-innovations, including regarding the role and importance of different societal actors. The increasing popularity of eco-innovation for weak sustainability has greatly influenced the power and roles of different social groups (Martínez-Alier, 1995). Researchers, especially techno-economic ones, industry players, and policy makers, have become expected to solve problems. Researchers should develop new knowledge that allows humanity to increase human-made capital and to compensate the loss of the natural one. New academic literature has focused on the relations between environment and innovation, creating a new terminology. Since the 1980s, new terms such as “eco-innovation,” “environmental innovation,” “green innovation,” “innovation for sustainability,” “socio-ecological innovation,” and “sustainable innovation” have appeared. The birth and diffusion of a new typology of terminology reflects the efforts of researchers to frame new knowledge about the relations between environment and innovation. These terms have also been widely used in non-academic communities, which indicates that other societal actors are involved in variously named attempts to promote “eco-innovation” (Schiederig *et al.*, 2012). Industry players have become promising agents of change. Firms are being asked to become environmental responsible and to develop and commercialize innovations that create value for firms and for the environment (Penna and Geels, 2012). Meanwhile, policy makers are expected to

² Here, I refer to the visions of society that are represented by the objectives of policies. Indeed, the strategies for achieving strong sustainability can still focus on weak sustainable measures. Consequently, in the case of climate policies, I am not arguing that the strong sustainability forges European climate policies.

create framework conditions that incentivize the diffusion of eco-innovations through better relations between academia and industry. The birth of the 'win-win' narrative (Porter and Linde, 1995) indicates that all these agents are linked by mutual positive influences, and that cooperation between them can create benefits for the whole society. In fact, the traditional "eco-innovation" evolution carries a strong normative value, because it calls for more cooperation and collaboration between the different actors, thereby shaping powers and relations within and between such social groups (Bowen and Fankhauser, 2011).

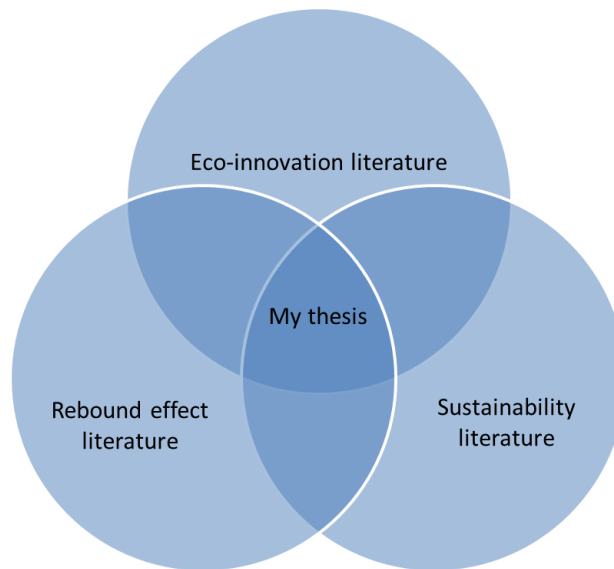
The conceptual analysis of the paradox is illuminated through the case of energy consumption for lighting. Several studies have investigated the dynamics of technological progress and consumption in the history of light. Two important findings from these studies appeared relevant for using this case as the empirical part of the present thesis. First, new lighting technologies have increased the efficiency with which energy is converted into light 1000-fold during the 20th century. Second, new uses of light in the 20th century increased the demand for it, with the result that energy consumption did not shrink. For that reason, the evolution of energy consumption for light is a good example of eco-innovations that increased weak sustainability, but did not improve strong sustainability. Furthermore, the lighting case is not relevant only for its past trends, but also for its future expectations. The lighting sector is at the dawn of a new revolution, driven by the new light-emitting diode (LED) technology in connection with the development of *smart* light systems. This technology expected to gain in popularity in many lighting market segments in 2015, which could make that year a turning point. As I have investigated in this thesis, many stakeholders have welcomed LED technology as a promising "eco" technology thanks to its capacity to improve the efficiency of energy conversion in lighting. As the thesis shows, however, LED is also expected to open up new opportunities for more intensive uses of light, and such opportunities will be exploited by a new class of lighting players that is expected to arise in the next decade. The conflict between the new opportunities for energy saving and the new ones for energy consumption in the use of light reflects the implications and consequences of the eco-innovation discussion in a lively case study.

Chapter 2 highlights the thesis' theoretical background by reviewing the history of the relations between innovation, society, and sustainability. Chapter 3 introduces the approach of my thesis, identifying how I addressed the various research issues, and how my four articles are connected in order to analyze the topic. Chapter 4 presents the four articles. Chapter 5 discusses the results that emerged from the findings of each paper, focusing both on the specific elements of the lighting sector and the general discussion. Chapter 6 concludes and highlights some specific issues that can be addressed to improve the quality of the results.

2 Innovation, “sustainabilities” and society

The theoretical foundation of the thesis is rooted in the eco-innovation literature, in which the existence of the paradox is discussed (Carrillo-Hermosilla *et al.*, 2009; Hekkert *et al.*, 2007). The discussion of the paradox develops through the intersection of three different literatures. Beyond the eco-innovation literature, my thesis includes the sustainability literature and the rebound effect literature. The sustainability literature provides the overall framework to understand the long-term evolution of the eco-innovation debate. The rebound effect literature is used to highlight complex long-term relations between technology, innovation, and sustainability (Herring, 2006; Jackson, 2009; Maxwell, 2011; Sorrell, 2007). Consequently, this chapter is divided in three sections, each of them dealing with a specific stream of literature. The first section presents the complexity of the eco-innovation debate, showing the lack of agreement about a common definition. The second and the third parts propose two different streams of literature that can help navigate such complexity. The second presents the rebound effect literature. The third presents the sustainability literature. I have combined these three literature streams to create a framework through which the eco-innovation dynamics can be discussed.

Figure 1 Streams of literature



2.1 The eco-innovation literature

The aim of this section is not to review the existent eco-innovation literature, but to highlight the complexity and the existence of different positions that generate the conceptual complexity in defining eco-innovation. Innovation emerged as a specific field of research in the 1960s (Fagerberg, 2009) and has grown in popularity

since. The seminal works of Schumpeter provided a first classification and understanding of the concept of innovation. Schumpeter identified five typologies of innovation: new products, new processes, new sources of supply, exploitation of new markets, new business models. Based on his work, a further classification was proposed between radical and incremental (or marginal), according to the degree of innovativeness with respect to the current stage (Fagerberg, 2009; Garcia and Calantone, 2002).

For the purpose of this thesis, two specific dynamics of the eco-innovation literature are relevant. The first, very briefly mentioned, highlights the birth of the systemic perspective on innovation. The second highlights the evolution of the use of the innovation literature in connection with the environmental question.

Godin (2007) dates the birth of the national innovation system perspective to the activities of OECD in the 1960s, even if the subject's academic popularity is thanks to the work of Freeman (1982, 1987) and Lundvall (1992). The system innovation literature became more popular and developed in a number of forms and variants (Bergek *et al.*, 2008; Cooke, 2001; Edquist, 2001; Fagerberg and Verspagen, 2009; Hekkert *et al.*, 2007; Lundvall *et al.*, 2002; Malerba, 2005). It is beyond the scope of the present thesis to review this consistent body of literature. For the purpose of the thesis, it is important to highlight how the development of innovations is highly dependent on the interactions of several elements in the society. The main outcome of this literature is that the pace and direction of innovative activities depends on the framework conditions in which actors interact. The systemic approach more clearly introduced the need for coordination and cooperation among different actors in order to encourage the development of specific innovations. Indeed other streams of literature highlighted the systemic dimension of innovation, and therefore have been partially included in the articles. For example, the technological foresight literature points out how technologies are intertwined with societies. This literature highlights the evaluative power of a society; that is, the ability to shape the criteria through which innovations are classified as *good* or *bad* (Schot *et al.*, 1994). Such evaluation influences the innovative processes (Kaplan and Tripsas, 2008), because promising innovations can easily attract the attention of policy makers, industry players, and other societal actors (European Commission, 2004). Therefore, “*we get the technologies we deserved*” (Bijker and Law, 1994, p. 3). Another important contribution comes from the socio-technical literature, in which a technology is actually understood in terms of the practices associated to (Marletto, 2014; Smith, 2007; Smith *et al.*, 2005). Therefore, when we talk about technology, we are actually talking about a society's development, diffusion, and use of technologies (Bijker, 1997).

The second branch focuses on the birth of the sustainability question in connection with the innovation literature. Schiederig *et al.* (2012) date the birth of the eco-innovation terminology to the beginning of the 1990s. Van Dieren (1995) dates the start of a concrete public debate on eco-innovation to the 1972 UN Stockholm Conference on the Human Environment³. Starting with the new millennium, this literature quickly

³ In the final declaration, the participants stated that “*man must use knowledge to build, in collaboration with nature, a better environment. To defend and improve the human environment for present and future generations has become an imperative goal for mankind – a goal to be pursued together with, and in harmony with, the established and fundamental goals of peace and of worldwide economic and social development.*”

evolved and many different, and somewhat contrasting, definitions arose, providing a complex picture of the relations between innovation and environment. A first position highlights the importance of eco-innovation for business. Among many others, Fussler and James (1996) proposed one of the first definition of eco-innovation as *“new products and processes which provide customer and business value but significantly decrease environmental impacts”* (as cited in Schiederig et al., 2012). Along the same line, MM Andersen defined eco-innovations as *“Innovations which are able to attract green rents on the market.”* (2008) that *“... makes no claim on the “greenness” of various innovations.”* (2008, p. 5).

A second position reflects the importance of eco-efficiency as main criterion of evaluation of eco-innovation. I already indicated the definition proposed by Kemp and Pearson. Similarly, the Europe Innova Panel (2006) stated that *“eco-innovation means the creation of... [innovations] with a life-cycle-wide minimal use of natural resources (material including energy carriers, and surface area) per unit output, and a minimal release of toxic substances”* (p.2). More explicitly, Foxon and MM Andersen (2009) indicated that *“the concept of eco-efficiency is closely related to the eco-innovation concept, and has been a pioneering concept in linking up environmental performance to economic performance.”* (p. 16). The eco-efficiency position has been stretched up to the case of “zero impact eco-innovations” (Business for the Environment, 2013; Deloitte, 2012; Schiederig et al., 2012) which can achieve the complete dematerialization of economy.

Other scholars indicated that the eco-efficiency approach may be not effective in reducing the environmental burden, because *“its goals, however admirable, are often regarded as insufficient in so far as increases in environmental efficiency tend to be erased by subsequent growth (rebound effect)”* (Carrillo-Hermosilla et al., 2010, p. 1076) and they call for more radical eco-innovation which can pursue wide societal transformations (Geels, 2011). Other authors root the eco-innovation definition in a more ecological domain. For instance, Rennings (2000) indicated that eco-innovation should *“contribute to a reduction of environmental burdens or to ecologically specified sustainability targets”* (p. 322), and he identified four typologies of eco-innovation: technological, organizational, institutional, and social.

The difficulty to grasp a common definition of eco-innovation is also due to the terminological confusion that arose about eco-innovation and the alternative terminologies that appeared in literature. A stream of scholars does not identify conceptual differences between the different terminologies. For instance, Schiederig et al. (2010) indicated that eco-innovation is a synonym of environmental innovation and green innovation. Hellström (2007) used eco-innovation as synonym for “environmentally sustainable innovation”. Similarly Rennings (2000), Bernauer et al. (2006), Oltra et al. (2008) , and De Marchi (2012) used eco-innovation as abbreviation for environmental innovation. Slightly differently, Rennings (2000), Pujari (2006) and MM Andersen (2010) used eco-innovation as synonym of green innovation. Other authors claimed conceptual differences between the terms. As example, Ekins (2010) indicated eco-innovation as *“a sub-class of innovation, the intersection between economic and environmental innovation”* (p. 269).

Fewer differences are showed about the motivational aspect that is not generally considered a prerequisite of eco-innovation (Carrillo-Hermosilla et al., 2010). For example, eco-innovation *“does not have to be developed*

with the goal of reducing the environmental burden” (Driessen and Hillebrand, 2002 p. 344), because it “may also occur as a side effect of other goals, such as reducing production costs” (OECD, 2009).

The complexity of the eco-innovation debate makes it almost impossible to sum up a common position. I argue that, in order to clarify this concept, two other streams of literature need to be included: the sustainability literature and the rebound effect one. The next sections present both of them.

2.2 The sustainability literature

The rise of the eco-innovation discussion is deeply rooted in the debate regarding the sustainability of long-term economic growth, which dates back to the late 18th and early 19th century, with the work of Thomas Robert Malthus (1798) and John Stuart Mill (1848). Malthus pointed out that population could grow beyond the Earth’s capacity to produce subsistence for humanity, while Mill was the first to propose a steady-state economy given the finite resource of the Earth.

In the 20th century, Boulding (1966), Georgescu-Roegen (1971), Meadows *et al.* (1972), and Daly (1973) provided further insights into the concept of limit in the economic process. Boulding used the Spaceship Earth metaphor to indicate the state in which the crew (the humanity) of a spaceship (the Earth) has to live with finite resources. Boulding confronted this close circular economy (the “spaceship economy”) with the current limitless “cowboy economy” and concluded that the future economy might look much more like the spaceship economy than the cowboy one. Boulding, and especially Georgescu-Roegen a few years later, pointed out that the second law of thermodynamics (the entropy law) governs all human processes, including the economic one. In their view, any economic activity consumes available free energy and transforms it into bound energy. A year later, in 1972, Meadows *et al.* published the well-known “The limits to growth” publication in which they presented computer modeling scenarios based on exponential economic and population growth in a context of limited resources. The authors concluded that some of these scenarios could lead to the collapse of human society, due to the deprivation of resources. Daly, the editor of the famous book entitled “Towards a steady-state economy”, proposed a specific steady-state economy that could cope with the limits to growth scenario.

I argue that the core contribution of the “degrowth” authors was to highlight that the economic process is related to the physical dimensions of economics. Consequently, the economic process is always dependent on the availability of energy and physical resources. This is not a trivial point, because the dominant neoclassical economy literature proposed a highly formalized modeling of economy in which physical dimension was absent. Creating space for such a discussion allows the literature to question the concept of unlimited growth in a context of potential resource depletions – a scenario that may have brought human society towards the collapse (Diamond, 2011).

The degrowth position has been widely criticized. Barry Commoner’s book “The Closing Circle” (1971) was considered the first answer to the degrowth position. He suggested that environmental problems are due to the current state of technology rather than the dynamics of population. The work of Commoner, and that of

Ehrlich and Holdren (1972), suggested using the “IPAT” equation to identify the environmental impact of human society. This formula indicates that the environmental impacts (I) of humanity result from the interaction of population (P), affluence (A) and technology (T). Discussions and debates have arisen regarding this formula, and the IPAT discussion has given technology a central role in the debate about the causes of environmental degradation. Solow (1973), Cole (1973), and Beckerman (1974) are among the popular scholars on this topic. It is beyond the scope of this thesis to summarize all of the various positions and critics in that literature (for a short review, see Cole, 1999). However, the common criticism of these authors was that the degrowth position underestimates the role of technology in making the economic process more efficient. Consequently, these scholars suggested that technological progress can reconcile environmental conservation and economic growth. A second strand of critiques claimed that the degrowth literature was a new form of eco-fascism that reduced people’s freedom of choice (Tukker *et al.*, 2008) and gave the elites the power to choose “who consumes what” (Bonaiuti, 2012; Raskin, 2008).

The definition of the sustainable development (Brundtland, 1987) concept was a milestone in such debate. In the Brundtland report, technology was acknowledged both as a risk and a potential solution for environmental sustainability (Panseira, 2012). The report proposed an identification of the concept of limits, based on the current state of technology and the current forms of social organizations. Consequently, among the different policy prescriptions, the Brundtland report explicitly expressed the need to develop emerging technologies that could improve the efficiency of the economic process.

Although the concept of sustainable development became very popular, it did not solve the contrast between the different positions. Convergence was achieved regarding the need to consider the environmental dimension as an explicit form of capital different from the human-made one (Arrow *et al.*, 2004). Nevertheless, the capacity of human beings to stretch the capability to transform natural capital into human-made capital through innovation remained at stake. For the sake of simplicity, the concepts of sustainability represented in this debate can be summarized as the weak and the strong one (Castro, 2004). In the weak definition, sustainability is defined as the capacity to not decrease the sum of natural and human-made capitals. In the strong definition, sustainability depends on the preservation of a critical amount of natural capital that cannot be converted in human-made capital. From the weak perspective, efficient conversion of natural capital in human-made capital is important. In the strong definition, sustainability implies the conservation of a critical amount of natural capital.

The two concepts of sustainability carry different visions of society. Advocates of weak sustainability argue that the concept of sustainability, by definition, depends on the state of knowledge and technology of humanity. The philosophical background lays in the idea that sustainability is an anthropocentric concept – our planet, as a physical entity, will survive. The question is whether human beings will be able to survive (or to increase the quality of life) among a rapid degradation of the natural environment. Therefore, sustainability shall be always understood as the capability of human beings (that is, human knowledge and capital) to cope with the surrounding environment. Advocates of strong sustainability may have either an anthropocentric or eco-centric view, because the preservation of a natural capital can be considered essential to save humanity (the

anthropocentric view) or can represent a view in which nature and environment have the same ontological dignity of the human being (the eco-centric view).

Through the articles that comprise this thesis, I argue that the weak sustainable perspective became the dominant position and forged the concept of eco-innovation. The next step is to briefly report the literature about relations between innovation (that is, efficiency in a wide context) and consumption, an issue that is harshly debated in the rebound effect literature.

2.3 The rebound effect literature

The relations between innovation and consumption had already been investigated before the birth of the environmental question. Jevons (1865) was the first to note that an increase of efficiency in the usage of a specific resource may actually increase the consumption of that resource. The interest in the literature in Jevons' coal question was the origin of the literature about the paradox, and the discussion developed slowly before the emergence of the sustainability question in the 1980s (Domar, 1961; Hotelling, 1931).

This literature was fueled by the growth/degrowth and sustainability debates because innovation, which actually increased efficiency, became a strategy with which to pursue sustainability (Herring, 1996). Among the most influential authors were Daniel Khazzom (1980), Krier and Gilette (1985), Brookes (1990, 1992), Greenhalgh (1990), and Saunders (1992), who deeply questioned the correspondence between increasing efficiency (in energy use) and reduction in (energy) consumption. These positions were fiercely opposed by other scholars, such as Lovins (1988) and Grubb (1990), who criticized the first rebound literature by identifying methodological flaws and an excessive evaluation of the dimension of the phenomenon. The debate about the relations between innovation (efficiency) and environment evolved over the time, including other sector and branches. For instance, the psychology literature has investigated how the human mind reacts when a new eco-efficient technology is developed. While some authors have identified a positive commitment towards saving resources when more efficient innovations are in use, others have claimed that greener technologies make people less concerned about environmental behaviors (Longoni *et al.*, 2014; Lorenzoni *et al.*, 2007; Peters *et al.*, 2012). Overall, there is no agreement about the importance of addressing the rebound effect, also because of methodological complexity (Sorrell, 2007).

The sustainability and rebound literatures provide important insights which can help to better understand the eco-innovation concept. The discussion chapter explains in the details the connection and the implications of such integration. In a nutshell, the sustainability literature clarifies the different visions and purposes of eco-innovation, while the rebound literature provides further understanding of the effects of different typologies of eco-innovation in respect to the sustainability purposes.

3 Thesis design and analysis approach

This section provides an overview of the overall research design and how the analyses in the different articles included in the thesis were designed to contribute to the main discussions. As shown in this chapter, the discussion is addressed through a combination of empirical-based and conceptual-based approaches. The chapter is organized into four different parts. The first part clarifies the main research question and the scope of the discussion. The second part indicates why the energy consumption for lighting was a suitable empirical case for discussion. The third part highlights the overall theoretical framework in which the discussion lies. The fourth and final part presents the contribution of each article to the overall research question. However, this chapter does not present the specific methodology used in each article, because these are presented in the articles themselves.

The main aim of the thesis is to propose a formulation of eco-innovation that overcomes the paradox in the relations between innovation and environment. Therefore, the thesis proposes the following main research question:

“How can the eco-innovation discourse overcome the supposed paradox between environment and innovation, in order to ensure that innovations improve strong sustainability?”

This research question has been addressed through various passages. The thesis starts by illustrating the innovative patterns that take place in the lighting market and that have dramatically increased the energy efficiency of the provision of light. Second, the analysis turns on understanding of the characteristics of the eco-innovation dimension, both in the eco-innovation discourse and in the lighting one, in order to frame the dynamics of the lighting case in terms of eco-innovation. Third, the paradox is explicitly introduced by investigating that the eco-innovation dynamics which increased the efficiency of the provision of light, also increased the consumption of energy. Fourth, I focused on conceptualizing a new definition of eco-innovation that could overcome the paradox, and on analyzing its implications for society.

The thesis developed a long-time perspective, which is essential for understanding wider connections between society, innovation, and environment. Accordingly, it includes a historical study, a focus on current dynamics, and a future-looking case study. The historical part is used to show that weak sustainability did not ensure strong sustainability. The future part shows that other development trends and dynamics are present in the lighting case and warn about the potential unsustainable effects of new promising eco-innovations. Moreover, the thesis indicates potential alternative pathways to reduce the consumption of energy for light.

The conceptual discussion of eco-innovation has been applied to the case of energy consumption for lighting. I chose this case for four main reasons:

- The lighting sector is an extreme case of efficiency increase. In the last century alone, efficiency in the production of light has increased a thousand fold. It represents a good case to confute the idea that increasing efficiency reduces consumption.

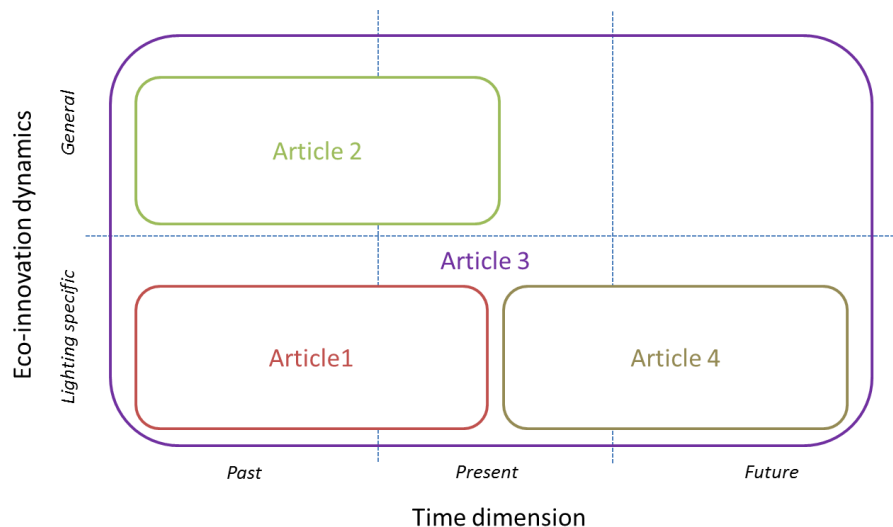
- The lighting sector is expected to experience a new technological breakthrough based on the diffusion of new LED lamps, which are expected to improve energy efficiency in the provision of light (Navigant Consulting Inc., 2012b). LED is widely recognized by several lighting stakeholders as a relevant eco-innovation that is expected to deliver environmental benefits.
- Several studies indicate that there are important potentialities for energy saving in the provision of light (Bertoldi and Atanasiu, 2010; EPA, 2011; Verify Markets, 2011).
- Policy makers indicate that lighting is one of the strategic sectors for reducing energy consumption (European Commission, 2011; TEM, 2005), showing that this sector is high on political agendas.

The two more practical aspects noted below also make this case a good test:

- The lighting sector showed a strong oligopolistic structure, which makes it easier to track the evolution of the most relevant lighting technologies (Bright, 1949; Loebner, 1976) throughout the 20th century. Therefore, the quality of the historical analysis gained an advantage from this specific market structure.
- Many studies have analyzed the rebound effect for lighting (Nordhaus, 1998; Tsao et al., 2010). Such studies provide important data about the dynamics of technology and consumption throughout history.

So far, I have defined a line of research based on two dimensions, through which my analysis was performed: (i) the time dimension (past, present, future) and (ii) the main focus (lighting eco-innovation vs. general eco-innovation). The combination of the two dimensions provides six quadrants. Figure 2 indicates how the four articles cover the six quadrants.

Figure 2 Areas of research and position of articles



Each article, in addition, has also its own specific theoretical background (see Table 1). The need to have a specific theoretical background for each article was due to the structure of the thesis based on the articles. Peer-reviewed articles must have their own proper “dignity” and must be considered as stand-alone

publications. Therefore, each article focused on a specific research question that was complementary to that of the thesis overall. In this sense, complementary means that specific theoretical backgrounds were needed, even if they were not included in the discussion of the main question of the thesis. Therefore, the methodological issue was to design articles that were both relevant as individual works and connected with the overall research topic.

Article 1 uses sectorial innovation system literature (Breschi *et al.*, 2000; Malerba and Orsenigo, 1997) to analyze the evolution of technological regimes in the lighting sector. Article 2 uses the Kuhnian perspective of the evolution of scientific knowledge (Kuhn, 1962; Struan, 2006). Article 3 uses a discourse analysis perspective (Hajer, 2000; Kuhn, 1962; Nicolini, 2012) to understand the role of actors and narratives in shaping innovation. Article 4 uses some insights from the socio-technical analysis literature (Bijker and Law, 1994), the technological foresight one (Brown *et al.*, 2000) and the rebound effect one (Sorrell, 2007) to highlight the role of practices in shaping uses of future lighting technologies and their impacts on energy consumption.

Table 1 Status of articles

Article	Title	Main literature	Publication stage
1	Non-disruptive regime changes – the case of competing energy efficient lighting trajectories	Sectorial Innovation System; Evolutionary Economics	Under review in Environmental Innovation and Societal Transition
2	Unveiling scientific communities around sustainability. A bibliometric journey around sustainable terms	Eco-innovation; Discourse analysis; Thomas Kuhn	Advanced draft
3	Beyond unsustainable eco-innovation: the role of narratives in the evolution of the lighting sector	Eco-innovation; Sustainability, Rebound effect; Discourse Analysis;	Published in Technological Forecasting and Social Change.
4	The green journey of indoor light and lighting. Future Visions among professional experts.	Eco-innovation; Rebound effect	Advanced draft

The last part of this chapter briefly introduces each article and positions them in respect to Figure 2. Full texts are presented in the next chapter.

Article 1

Article 1 used the sectorial system of innovation literature to analyze the long-term innovative patterns of new lighting technologies throughout the 20th century. The main “own” contribution of Article 1 was to show that the different lighting technologies did not necessarily develop according to one dominating regime. They can develop in different alternative regimes for shorter or longer periods of time. In the specific case of lighting, the combination of oligopolistic strategies with the changing (and increasing) importance of energy efficiency through the decades weakened the dominance of the incandescent regime, without radical breakthroughs. This aspect has been highlighted, as the majority of literature suggests that radical changes are needed to

escape dominant lock-ins. The potential for incremental ways to disrupt lock-ins provides policy makers with alternative policy opportunities to escape from undesirable technological patterns.

In connection to the Thesis, Article 1 provides the empirical background for the discussion of the lighting case study. In fact, Article 1 illustrates how increasing energy efficiency played a central role in a large part of the innovation processes related to the provision of light. In particular, energy efficiency was of central importance for the non-residential lighting markets already in the 1940s. Thus, when the energy agenda became intertwined with the environmental one, starting from the 1970s, energy efficiency became a dominant force that shaped the diffusion of more efficient lighting technologies even in the residential lighting market. Article 1 represented a necessary step for the discussion of the Thesis, for two reasons: First, it provides a detailed description of the innovative process, which eliminated the possibility that the increase of energy consumption in the provision of light was not the result of a slow increase of energy efficiency. Second, it indicates that energy efficiency gained popularity as a way to integrate both environmental and energy issues, paving the way for the formulation of the ‘green growth’ narrative, as done in Article 3.

Nevertheless, Article 1 did neither introduce the eco-innovation discussion nor the concept of paradox, because two more fundamental steps were needed: i) the understanding of the eco-innovation dimension, and its connection with efficiency (Article 2); ii) a more detailed illustration of the interplays between eco-efficiency and energy consumption in the provision of light (Article 3).

Article 2

Article 2 performs a bibliometric analysis to study the scientific literature and discourse on innovation and sustainability. The main “own” contribution of Article 1 was to study meanings of and communities around four nowadays popular sustainable terms (eco-innovation, environmental innovation, green innovation, and sustainable innovation). The analysis showed that the terms only partially overlap in their meanings and scientific communities. The main conclusion was that the eco-innovation discourse is a field of contested positions about sustainability and innovation.

In connection to the Thesis, Article 2 provides the literature background and review for the discussion of the eco-innovation dimension. In detail, Article 2 provides two important contributions. First, the evidence about the different meanings and scientific communities around eco-innovation justifies the analysis of the different narratives about innovation and sustainability, as performed in Article 3. Second, the advanced bibliometric analysis complemented the traditional literature search and review for the Thesis, providing a very deep understanding of the relations between innovation and sustainability in the scientific literature. This element was essential to further conceptualize the eco-innovation dimension, as done in the discussion section of the Thesis.

Article 2 is at the advanced draft stage. The co-authors and I expect to further analyze the degree of homogeneity of the communities within each sustainable term. In fact, at the present stage of the analysis, we have not considered explicitly the possibility that each of the specific terms can be used with different meanings.

Article 3

Article 3 provides a framework to illustrate the different narratives about sustainability and innovation, and uses it to analyze the perspectives and implications in the lighting area. More specifically, Article 3 identifies six competing narratives along two axes: i) typology of innovation; ii) effect on demand. The Green Growth narrative is identified as the current dominant one, and it is based on the weak sustainability concept. Risks and limitations of such narrative are highlighted, and an alternative narrative, which can ensure reduction of energy consumption for lighting, is proposed and discussed.

In connection to my Thesis, Article 3 provides the central proposition of my discussion, because it connects the conceptual-discursive perspectives of eco-innovation and sustainability with the empirical case of the lighting area. By criticizing the Green Growth narrative and supporting a narrative based on the concept of strong sustainability, Article 3 provides the theoretical and empirical framework used to define the new conceptualization of eco-innovation in the discussion of the Thesis.

Article 3 is thought to follow up on the findings of Article 1 and 2. From Article 2, Article 3 takes the concept of the framework to analyze the (lighting) narratives, where contested positions about sustainability are present. Indeed, Article 2 shows that terms are differently shaped by different communities. Therefore the definition of a framework to place the different narratives in a space composed by innovation and sustainability would have been a useful tool to understand patterns of evolution of the eco-innovation discourse. From Article 1, Article 3 takes the current positioning of technology, as the intersection of efficiency and environment. Therefore, Article 1 provides a detailed description of the innovative dynamics, which are presented in the X-axis of the proposed framework in Article 3.

Article 4

Article 4 analyzes the current expectations about the future of lighting under the lens of the new eco-innovation conceptualization. The analysis is limited to the non-residential indoor market, because the other market segments show technological dynamics that are too different. For instance, incandescent and halogen technologies are still dominant in the residential market, while they have almost disappeared in other markets. This implies that there is still a huge space for promoting more efficient lighting technologies in the residential market, because of the poor energy performance of the incandescent and halogen technologies.

The proposed eco-innovation perspective strongly influenced the used methodology. The article uses a cognitive methodology in which interviewees were asked to evaluate the energy-saving potential of specific elements, and to identify relevant relations among the elements. Identifying relations is essential in the proposed eco-innovation perspective, because the aim is not to assess a specific innovation, but to understand overall changes at the level of society. Therefore, Article 4 was an empirical test for the new conceptualizations of eco-innovation.

Article 4 is at the stage of advanced draft. The co-authors and I are evaluating the possibility to replicate the study in The Netherlands, a country with similar societal dynamics as in Denmark, but with an important

difference regarding the lighting discourse. Whilst Denmark has no relevant incumbents, the main headquarters of Philips are located in The Netherlands.

4 Papers

Article 1. Non-disruptive regime changes – the case of competing energy efficient lighting trajectories

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Abstract

Technologies within an industry are expected to follow similar sectorial patterns of innovation; however, such similar patterns did not occur for the three most recent promising technologies in energy efficient lighting. Both fluorescent tubes (FL) and compact fluorescent lamps (CFL) developed within the lighting industry and faced relevant oligopolistic barriers, but each showed very different patterns of diffusion because the importance of energy efficiency differs between the residential and non-residential lighting markets. Light-emitting diode (LED) technology followed a different pattern. This technology developed outside the traditional lighting markets for almost a century and did not face the same oligopolistic barriers. Only in the new millennium did LED become a relevant competitor in the lighting market, and quickly developing in a context in which the incandescent regime was already weakened by competition with CFL and FL. We conclude that LED followed an “incremental” way to weaken dominant regimes through diffusing in complementary markets and circumventing the oligopolistic barriers. In addition, such a feature further weakened the oligopolistic power of the lighting market by allowing new players from the semiconductor industry to enter the lighting arena.

Keywords: lighting technologies, energy efficiency, sectorial innovation, technological regimes, non-disruptive changes, eco-innovation

1. Introduction

Policy makers are increasingly interested in new eco-efficient lighting technologies to decrease energy consumption, reduce energy costs, and create new business opportunities (European Commission, 2011). In the previous century, the fluorescent light (FL) and its residential application, compact fluorescent lamps (CFL), were considered the most promising future technologies, but today attention is shifting towards light emitting diode (LED) technology (Chappin & Afman, 2013). Insight into the innovation trajectories of eco-friendly technologies is necessary to adequately support their development, implementation, and diffusion (Alkemade et al., 2011; Quitzow et al., 2014). This insight is especially needed in the case of alternative lighting technologies because their development seems to deviate from the patterns predicted by theory.

More specifically, the literature describes how technologies within an industry usually develop under the same *technological regime*, and display similar sectorial patterns of innovative activities (Breschi et al., 2000). These similarities arise because the main determinants of innovation, such as technological opportunities, the appropriation of innovations, the cumulativeness of technological advances, and the properties of the knowledge base, are similar for all firms within an industry. In addition, theory predicts that changes in these patterns arise mainly as a result of major (technological) discontinuities that disrupt the industry. As we demonstrate in this paper, the three alternative lighting technologies, FL, CFL, and LED, have shown different patterns of innovative activities despite similarities in the determinants of innovation; therefore, we can observe multiple technological regimes within the same industry.

These three technologies have many common characteristics because they were developed through long-term intensive R&D processes in an oligopolistic context in which General Electric (GE) played a leading role, especially in the R&D phase. The similarities among FL, CFL, and LED suggest that these technologies developed within the same or a similar technological learning regime, and therefore showed similar patterns of innovative activity (Malerba & Orsenigo, 1997; Pavitt, 1984). However, once introduced to the market, FL and LED quickly became dominant, but CFL struggled for decades. Observing these differences between expected and actual patterns of diffusion, we posed our main research question: *Why did CFL show a different pattern of innovative activity than FL and LED despite similarities in the main determinants of innovation for these technologies?*

To address this question, we conducted an in-depth historical case study based on the analysis of available academic and non-academic documentation produced in the last century. The lighting market's oligopolistic structure narrowed the most important players and sources to be tracked, easing our analysis.

This paper is organized as follows: Section 2 defines the theoretical and methodological framework. Section 3 presents the history of the alternative lighting technologies. Section 4 discusses the different technological regimes, and section 5 provides conclusions.

2. Innovation dynamics and profit-driven industry evolution

Profit is the main driver of a firm's innovative efforts (Jacobides & Winter, 2007). Schumpeter pointed out that firms develop both short-term and long-term profit strategies (Cantwell, 2000) to seize the value of new innovation, commonly defined as a new combination of elements with a final value superior to the sum of the value of the individual elements (Schumpeter, 1934). Short-term profit strategies aim to seize current profits in

the market through decisions about price and quantity (Jacobides, Knudsen, & Augier, 2006) and represent firms' bargaining power when resources are unevenly distributed (Teece, 1986). Long-term profit strategies focus on the generation of novelties in a context of uncertainty (Langlois, 2007) to destroy current sources of profit and create potential new ones. This strategy is the well-known Schumpeterian concept of creative destruction that refers to an innovations' disruptive effect on profit flows (Cantwell, 2000; Lundvall et al., 2002).

To develop its portfolio of short- and long-term strategies, a firm considers both the potential value of a future innovation, the actual chance of capturing this value, and the innovation's impact on current profit flows. This relation between short- and long-term strategies leads to a strategic dilemma for the firm: On the one hand, a consistent flow of short-term profits is necessary to generate resources to sustain long-term strategies, but on the other hand, new innovations may hamper short-term profits, causing firms to shy away from developing them. Since firms have heterogeneous capabilities developed through cumulative patterns (Cantwell, 2000; Jacobides et al., 2012; Mowery, 2010), they develop complex, individual, and time-dependent (Jakopin & Klein, 2012) innovation strategies.

Schumpeter captured the complexity of innovation activities in different markets in two stereotypic market models, lately labeled as Mark I and Mark II (Breschi et al., 2000). The Mark I model highlights the role of newcomers who develop innovations that disrupt the incumbents' short-term profits (Chandy & Tellis, 2000). As soon as these newcomers stabilize the novelties they have brought to the market, they focus on short-term profits and become the new incumbents, creating space for other future newcomers (E. S. Andersen, 2012). The Mark II model highlights the role of stable oligopolistic incumbents as main innovative players (Mowery, 2010). Incumbents are dominant because they can exploit short-term profits and thus sustain new innovative efforts. Hence, market power is a means and not the reason for incumbents' dominance because in both models the locus of competitiveness is always innovative capacity. Recent literature has proposed combining Mark I and Mark II patterns into new market models in which technological evolution is depicted through the interaction of small and big players who mutually benefit from their different capabilities (M. M. Andersen, 2011).

The literature about the determinants of innovation and technological regimes has deepened Schumpeterian innovative patterns (Malerba & Orsenigo, 1997). The technological regime is defined as the combination of four determinants (appropriability, opportunity, cumulativeness, and knowledge base), whose combinations define the different Schumpeterian patterns. Therefore, the literature has connected the Schumpeterian patterns of innovation to the knowledge-based characteristics that occur at the sectorial level.

In this study, we observed a combination of patterns of innovation in the history of the lighting industry. Some incumbents, such as General Electric, played a pivotal role in developing new lighting technologies during the last century, but diffusion of these novelties depended mainly on the presence of newcomers. This intra-sectorial relationship between incumbents and newcomers differed for each technology even when commonalities were present. In the next section, we discuss the most salient historical facts that offer an explanation for these different diffusion patterns.

3. The history of competing lighting technologies

This section explores the several lighting technologies that have been developed over time (Edison Tech Center, 2013). First, we discuss the lighting market since the 1930s, when the first fluorescent tube was on the market, and then the development through the last century of the two most prominent modern indoor lighting technologies: the fluorescent light (both the traditional tubes and the compact fluorescents used in residential application) and the LED. Second, we analyze the observed patterns and strategies of innovation.

3.1 The quasi-monopolistic lighting sector at the beginning of the 20th century

In 1937, the year before the first fluorescent light was presented on the market, incandescent lamps had a share of nearly 96 percent of the electric lamp market (Bright & Maclaurin, 1943). The US firm, General Electric (GE), directly controlled 59.3 percent of the incandescent light market, and indirectly, almost 86.6 percent through its license program (see Table 2).

Table 2 Share of US market for large tungsten-filament lamps in 1937. Source (Bright & Maclaurin, 1943)*
See text for license explanations.

Firm	Market share (%)	GE license classification*
General Electric Co. (GE)	59.3	Licensors
Westinghouse Elec. & Manuf. Co. (WE)	19.0	A-type
Sylvania Elec. Prod. Inc.	4.4	B-type
Consolidated Elec. Lamp Co.	2.8	B-type
Ken-Rad Tube and Lamp Co.	1.1	B-type
Other 20 domestic firms	8.8	Unlicensed
Importers	4.6	Unlicensed

The A-type license granted a firm the right to sell any kind of lamp in any quantity, whereas the B-type granted the sale only of large incandescent lamps within specific limits (Bright & Maclaurin, 1943). Independent firms and importers accounted for less than 14 percent of the market. In addition, GE strengthened its position by: i) establishing mutual agreements with major foreign lamp producers who agreed to sell lamps exclusively in their own countries; ii) maintaining its unique position as the only firm to produce all necessary parts in-house, causing other firms to depend on GE or other external suppliers; iii) joining with Westinghouse (WE) to promote a lighting fixture association of hundreds of firms to control incandescent bulbs fixtures; and iv) creating partnerships with energy utilities to develop electric turbines and generators. In this period, the US lighting market was a clear example of a Mark II quasi-monopoly market with GE playing a leading role.

3.2 The emergence of the fluorescent light

The possibility of producing light through fluorescence was already known in the second half of the 19th century (Bright & Maclaurin, 1943), and the first prototypes appeared at the beginning of the 20th century,

thanks to the work of Peter Cooper Hewitt and Edmund Germer. For the first time, incandescence (lighting by heating) was not needed to generate light (Lowry, 1953).

GE acquired the first patents and hired Germer to develop further the fluorescent lamps (Peter et al., 2013). The plan was to reach a stable, reliable development stage before commercializing the innovation (Bright & Maclaurin, 1943). Despite this attempt to keep the development a secret, the first fluorescent lamp was exhibited at the 1938 New York World's Fair, after engineers and other specialized actors who knew high-efficient fluorescent prototypes were in development insisted that they be demonstrated (Bright & Maclaurin, 1943). The first fluorescent lamps met expectations. In fact, the first fluorescent tube had an efficacy of 30 lumens/watts and almost 1,000 hours of useful life (Inman, 1939), compared with the incandescent bulb's 14 lumens/watts. The diffusion of the incandescent bulb created three main issues that in turn increased interest in this new, more efficient lighting solution (Inman, 1939): (i) an increase in the cost of electricity; ii) problems with electrical wiring overload in many offices and retailers; and iii) an increase in indoor temperature because of heat dissipation from incandescent bulbs.

Following its success of the fair, GE and WE separately announced market introduction of the new fluorescent lamp in 1938, and the first 200,000 lamps quickly sold. But GE and its partners considered the new fluorescent lamp a risk (Bright & Maclaurin, 1943; Rogers, 1980) and kept their focus on incandescent technology while continuing to develop the fluorescent lamp.^{4,5} GE worried that an infant technology would hamper its image of affordability and would open space for competitors. Energy utilities were concerned that more energy efficient lighting solutions would harm their profits,⁶ and lighting-fixture manufactures worried about technical changes required by shifting from a bulb to a tube shape.

In 1940, Sylvania decided not to acquire a GE B-type license for the FL, but rather to develop its own version. Starting from an incandescent bulb market share of 4.4 percent in 1937, the company quickly obtained 20 percent of the new fluorescent market, becoming GE's first relevant competitor. In reaction, GE and WE increased their efforts in the new fluorescent market (Bright & Maclaurin, 1943). After World War II, many GE core patents expired and GE's licensing system was ruled a violation of anti-trust laws (Rogers, 1980). As a result, GE ended its agreement with WE, and many patents were licensed to competitors free of charge. GE's share in both the fluorescent and incandescent markets fell, and other players began to develop their own lamps and parts (Rogers, 1980).

⁴ *"The fluorescent Mazda lamp should not be presented as a light source which will reduce lighting costs."* GE statement of policy, 1939 (Bright, 1949, p. 404).

⁵ *"We will oppose the use of fluorescent lamps to reduce wattages."* WE internal policy (Bright, 1949, p. 404).

⁶ *"I am very, very much disturbed over the utility reactions which I am sure we are going to have as soon as we announce the longer, larger and higher wattage fluorescent lamps."* Internal memorandum of the GE lamp department to the GE lamp department executives (Bright, 1949, p. 402).

The market quickly grew from 200,000 fluorescent lamps sold in 1938 to 79.1 million in 1947 (Bright, 1949, p. 410), especially in the office and retailer markets. In 1951, fluorescent lamps produced more lighting, expressed in lumens per hour, than incandescent lights (Smithsonian Institution, 2014a). However, the popularity of the fluorescent tube did not reduce overall energy consumption (Fouquet & Pearson, 2006) because to appease utility companies, fluorescents were used to provide new lighting applications.

During the 1950s, fluorescent lamp technology improved considerably: Construction costs decreased and efficiency increased. As result, incandescent lamps disappeared from the non-residential lighting market, and fluorescent lamps rose from 42 million units sold in 1945 (5.3 percent of the sold incandescent lamps) to 284 million in 1974 (18.5 percent) (Rogers, 1980). However, in the residential market, incandescent technology continued to dominate.

3.3 The emergence of the CFL lamp

The oil crisis of the 1970s spurred firms to increase their efforts to create residential fluorescent solutions (U.S. DOE, 2006). GE announced the first spiral-shaped compact fluorescent light (CFL) in 1976, but decided to shelve the invention because of its high production costs⁷ (Kanellos, 2007), while working on further development. According to the 1980 U.S. national lighting report, the CFL did not appear in the list of recent lighting inventions through 1978 (Rogers, 1980). The spiral-shaped CFL was not commercialized until 1995 (Smithsonian Institution, 2014b) when Litetronics brought it to market (Litetronics, 2010). Meanwhile Philips introduced the first non-spiral CFL lamp in 1980 (Kanellos, 2007) at a price of 16 times that of a standard 100-watt bulb, and GE overcame a technological hurdle to produce a dimmable fluorescent lamp in 1988. Since the 1980s, production costs have decreased (Ellis et al., 2007; Iwafune, 2000; McDonald & Schrattenholzer, 2001) and worldwide CFL sales have risen from 80 million in 1990 to 365 million in 1997 and 1,800 million in 2006 (Iwafune, 2000; Weiss et al., 2008).

The CFL drew the attention of the U.S. residential lighting market beginning in the late 1990s. In 1997, the U.S. Environmental Protection Agency (EPA) expanded the ENERGY STAR® labeling program to residential light fixtures; the program aims to reduce energy consumption through voluntary labeling of products with the highest efficiency performances on the market. In 1999, EPA launched a specific ENERGY STAR® labeling program for screw-based CFLs (Calwell et al., 2001). During the same period, the Pacific Northwest National Laboratories (PPNL), a branch of the U.S. Department of Energy, introduced a project to promote the most promising CFLs, which helped many small overseas companies to advertise high-quality CFLs in the U.S. market. In addition, the contextual EU anti-dumping tariffs of up to 75 percent imposed on Asian CFL manufacturers (Calwell et al., 2001) encouraged many of those firms to shift their focus towards the U.S. market and increased competition.

⁷ Ed Hammer, leading GE scientist working on fluorescent solutions, remembered, *“I was told it could be a little better than an incandescent bulb, but that was about it . . . and the new lamp would have required 25 million of investment to be produced”* (Kanellos, 2007).

Simultaneously, California launched several initiatives to boost the CFL residential market in response to a serious reduction of the state's energy reserves and a subsequent 173 days of energy emergency in 2001. The multi-year "California Residential Lighting and Appliance Program" began in 1999 and aimed to reduce the price of CFLs and create a market. An example of the program's activities was a training program in new CFL solutions for 180 retail store employees. The Californian government also directly distributed 1.9 million CFL lamps to final users, advertised the CFL's benefits in the media, and increased electricity tariffs to stimulate market formation for the more energy-efficient lighting technology. As result of the combination of state and federal measures, the Californian market share of CFL rose from 1 percent in the final quarter of 2000 to 8 percent at the beginning of 2001 (Calwell et al., 2001; Iwafune, 2000). In 2001 alone, more than 10 million of CFLs were distributed through state programs (XENERGY Inc., 2002).

In the period 2006–2008, California authorities launched the "Upstream Lighting Program" (ULP) to reduce energy demand; 92 percent of the program's overall savings were achieved through CFLs solutions (Kema Inc., 2010). In 2006, 32 ENERGY STAR CFL programs were active, totaling \$50 million. In 2009, these programs had increased to 109, totaling \$252 million. The CFL market share reached 20 percent in 2009 (Swope, 2010), and 22 percent in 2010 (Navigant Consulting Inc., 2012a). Today, almost 100 ENERGY STAR manufacturing partners are active on the U.S. market, producing 1,600 unique CFL lamps. Including repackaging initiatives, the market includes 234 brands and over 4,500 CFL products (D&R International, 2010). More than 80 percent of CFL consumers have declared they are satisfied with the product (D&R International, 2010).

Future scenarios indicate that CFLs will achieve a market share of 60 percent in 2014, phasing out the traditional incandescent technology, but CFLs dominance beyond 2015 depends on the diffusion of the new LED technology. In the "non-LED" scenario, the CFL market share should stabilize around 60 percent, but in the LED scenario, LEDs should replace all the current lighting technologies. Interestingly, the phase-out of incandescent lamps can be expected to follow the same pattern despite the evolution of LEDs.

In the next section, we investigate further the evolution of LED technology, analyzing the long-term process of development and diffusion that allowed this technology to become the most promising one today.

3.4 The emergence of the LED light

In 1907, H. J. Round at Marconi Labs reported the "*curious phenomenon*" of cold light emission from a diode while working on a cat's whisker detector for the development of the radio (Schubert, 2003). In the 1920s in Russia's Central Radio Laboratory (CRL), Losev reported a detailed description of electroluminescence and potential uses for "*fast telegraphic and telephone communication, transmission of images and other applications*" (Daukantas, 2012, p.34), but Losev's death during the siege of Stalingrad in 1942 prevented his developing his intuition. After the Second World War, Bell Labs began working on more energy efficient telephone switches, replacing vacuum tubes with semiconductors. Semiconductors were interesting because of their radio amplifying properties, and the "curious" lighting properties were not investigated for several decades (Loebner, 1976). Not until the early 1950s did research by Bell Labs and Signal Corps Laboratories (SCL), a part of the US Army, better explain the relationship between amplifying and lighting properties. At that time the industry's priority was to develop electroluminescent, solid-state devices to substitute for the energy-

hungry cathode ray tube in televisions (Dempewolf, 1962). Even unsuccessful R&D efforts that may have focused on non-LED materials contributed to a deeper understanding of the electroluminescence phenomenon, knowledge that was later essential to develop LEDs.⁸

Following these failures, only a few large firms had enough resources to continue LED research. Among them was GE, whose rectifier department announced a major breakthrough in 1962 with the invention of both the first infrared and the first visible red LEDs. GE commercialized the first visible red LED in the same year. The lighting department was not the main actor in these developments, as Holonyak, the inventor of the first visible red,⁹ explained.

By 1962, all major firms were working on the new technology and exploring technological options closest to their existing knowledge bases. Hewlett-Packard (HP) developed an extensive research program to investigate 17 different semiconductor materials, and then focused on the Gallium arsenide phosphide (GaAsP) (Loebner, 1976). HP joined with Monsanto, the leading supplier of GaAsP, to start a LED technology program (Ashrafi, 2005) in 1962 to develop an LED alphanumeric display (Borden & Pighini, 1969). The collaboration did not last long, as both firms were concerned about becoming too dependent on one another. Monsanto produced the first commercial numeric display based on LED, the MAN-1A, and HP closely followed. Numeric displays were the first early market, and soon IBM introduced LED-based displays in CPU working activity indicators. Other markets followed, such as wristwatches, calculators, phones, optocouplers, and optical mice (Haitz & Tsao, 2011). The birth of the new LED display market created a very fluid context with new alliances (Busicom and Intel), spin-offs (Litronix from Monsanto), and newcomers from other markets.¹⁰

Meanwhile, researchers sought to develop the other primary colors, blue and yellow, to produce the full light spectrum (Borden & Pighini, 1969). In 1970, Craford, Holonyak's first graduate student, announced the invention of the first yellow LED along with an improved red LED at Monsanto Labs, and Bell Labs announced the first green LED (Rostky, 2001). Creating a blue LED was most challenging, because blue lies in the opposite

⁸ "Schon, a most prominent ZnS luminescence theorist, established two fundamental criteria which no contemporary LED designer can ignore ..." (Loebner, 1976, p. 685), and later, "We expected that the results [of LED and non-LED research]... would aid each other and increase fundamental understanding of electroluminescence in both materials" (Loebner, 1976, p. 686).

⁹ As Holonyak stated, "... and even though I'm getting some support from ... the Rectifier Department, it's taking me in the direction of something that will be a light emitter, which won't be as useful to him [the rectifier department] as it will be to the Lamps Department. That Lamps Department is now working out arrangements with other people to get back in this, because the LED has become really a lamp, and is beginning to do major things. And the Lamp Department at GE can no longer ignore that" (Ashrafi, 2005).

¹⁰ For instance, several LED companies entered the watch market, including Hughes Aircraft, National Semiconductor, Fairchild, and Texas Instrument.

light spectrum of red. RCA seemed to be the closest to developing blue LEDs when it announced a “bright violet” LED in 1972, but the company collapsed in the following years. The production of a new flat TV that could be hung on a wall like a painting had driven RCA’s efforts. Again, as with earlier attempts in the 1950s, replacing the cathode tube was the main reason for developing of electroluminescence applications.

In the 1970s, Monsanto, a pioneer in LED technology, quit the growing business and sold its activities to General Instrument (Monsanto ESP Riunion Website, 2012). At the same time, LED diffused in several lighting markets in which the full RGB spectrum was not needed, such as disco-lighting systems (“Saturn I-IV LED lighting systems”), exit signs, automobile central brake lamps (Daukantas, 2012; Moore, 1999), and traffic lights. The next breakthroughs occurred in 1989 when Cree announced the first blue LED and in 1993 when new Japanese entrant Nichia announced the first high-bright blue (the result of a research project at Nagoya University in 1981 [Daukantas, 2012]), and, consequently, the first white LED in 1996. In the 1980s, several other new Japanese players entered the market.

The scaling up of LED production in the 1980s and 1990s allowed the diffusion of a new more advanced manufacturing process called Metal Organic Chemical Vapour Deposition (MOCVD). Although this process, which had been known since the 1960s (Grodzinski et al., 1995; Samsung, 2004), was very expensive and sensitive to environmental conditions, it was the only option for mass production of very pure LED components, an essential condition to develop high-bright LEDs (Daukantas, 2012; Shimizu & Kudo, 2011). In the 1990s, the MOCVD technique allowed production of 25 lumens/watts for red and yellow LEDs, and six lumens/watts for blue and green LEDs, where other techniques could achieve only about one lumen/watt (Grodzinski et al., 1995).

The availability of all primary colors enabled new potential applications for LEDs. HP and Philips initiated a collaboration to investigate potential applications for the white LED in 1994, creating a joint venture two years later. At that time, LED technology was expected to achieve an efficacy of 50 lumens/watts by 2010. Consequently, LED was not considered a solution for the general lighting market because fluorescent technology was more efficacious (Haitz & Tsao, 2011), although LED could have potential applications for specific lighting markets.

This perspective drastically changed in 1999 when HP and Sandia National Laboratories presented revolutionary predictions indicating that LED could achieve up to 200 lumens/watts and manufacturing costs could be dramatically reduced (Haitz & Tsao, 2011). These new predictions, known as “the Haitz’s law,” suddenly changed the lighting industry and LED became a general lighting technology. As a result, players moved into that market. In a joint venture with HP (through Agilent), Philips created Lumileds in 1999 to develop and commercialize high-powered, high-efficiency LEDs for a wide range of uses. In 2007, Philips acquired 100 percent of Lumileds. Similarly, OSRAM took over the semiconductors division from Siemens in 1999, creating OSRAM Opto Semiconductors through a partnership. In 2001, OSRAM took full control of the company to offer a full range of general lighting LED solutions. Both firms entered the LED general lighting market by internalizing specific semiconductor capabilities.

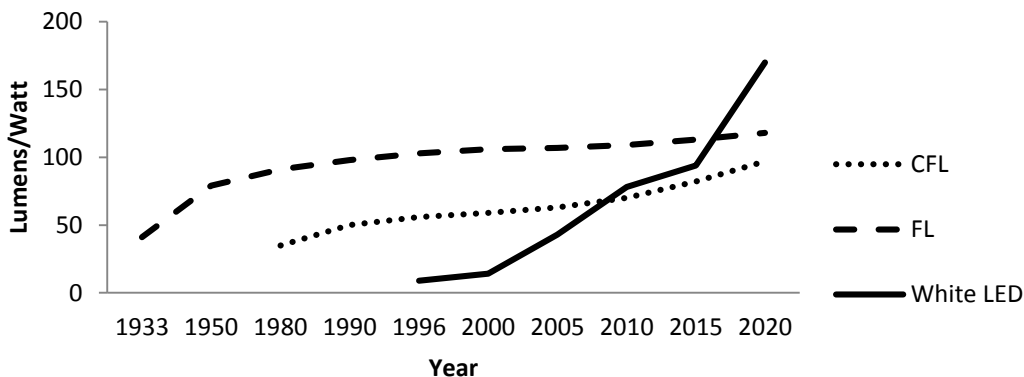
Following new expectations about LED lighting technology, private and public R&D investments in the 2000s and 2010s nearly doubled compared with previous industry market forecasts (Haitz & Tsao, 2011). Haitz and Tsao noted that the U.S. government decided to fund both LED and OLED technologies, and subsequently could not sustain the \$500 million in R&D funds required to achieve a white LED efficacy of 150/200 lumens within 10 years (Haitz & Tsao, 2011). As a result, Asian firms filled the technological gaps in LED, and many, including Nichia, Samsung, LG Innotek, Seoul Semiconductor, Sharp, and Toyoda Gosei, obtained relevant positions in today's market. The value of the LED market is expected to stabilize because the price reduction in LED components will compensate for the increase in quantity sold (Peters & Wright, 2012). Among market segments, backlight and mobile applications are expected to quickly decrease, and general lighting applications quickly increase.

4. Discussion – the different technological regimes

At the beginning of the 20th century, there was a great need for more efficient solutions in non-residential indoor markets (where fluorescent technology developed) and in the electronic market (where LED developed). Market dynamics rewarded energy efficient innovations, and big players had a competitive advantage in developing new technologies, based on intensive long-term R&D efforts, that could replace incandescence. Efficiency did not play as large role in the residential lighting market until the oil crisis of the 1970s, when the CFL was produced for the first time, and again in the late 1990s with increasing concerns about sustainability and energy security. Figure 3 represents the evolution of efficiency over time for these three technologies.

Figure 3 Energy efficiency of the most popular indoor lighting technologies.

Source: Own elaboration on Craford (2007), Narukawa et al. (2010), Navigant Consulting Inc. (2012b, 2009) and U.S. DOE (n.d.)



White LED development skyrocketed in the 1990s with the publication of the Haitz's law, which proposed a scenario in which LED could outperform fluorescent technology, opening the general lighting market to this technology. This new long-term perspective created a new wave of investments that actually fueled the recent dramatic improvements in LED efficiency.

The history of lighting technologies shows the importance of the market structures in which any technology develops. The fluorescent technology in residential and non-residential segments experienced strong

oligopolistic barriers. The diffusion of the tubes in the 40s was possible thanks to the combination of a strong demand for high efficiency solutions with the disruption of the dominant position due to antitrust prescriptions, expiration of patents, and aggressive competitors. GE had based its profits on exploitation of the incandescent bulb, and therefore, did not want to diffuse new technologies that could hamper its flow of profits.¹¹ Only when GE was weakened, could Sylvania start an aggressive strategy to diffuse fluorescent tubes in the lighting market, and force GE to answer. Similar dynamics happened several decades later with the compact fluorescent lamp. Once new competitors penetrated the market thanks to incumbents' weaknesses, the CFL was diffused. Unlike the previous lighting technology, LED technology did not experience the same weakness among incumbents because LED has the characteristics of a general purpose technology (Shimizu & Kudo, 2011) and could diffuse in complementary markets (see Table 3).

Table 3 LEDs and markets.

Source: Own elaboration

Decade	LED primary colors	Main markets and applications
1960s	Red	None
1970s	Red, Green	Alphanumeric red display
1980s	Red, Green	Brake lamps, disco-lighting systems
1990s	Red, Green, Blue	Traffic lights, automotive industry, exit signs, specialized non-white lighting
2000s	White	Backlighting illumination, specialized white lighting
2010s	White	Backlighting illumination, general lighting

Although the lighting market was highly oligopolistic, LED improved because it could diffuse in other markets. Once the technology matured in the 1990s, it became a potential solution for the general lighting market. Table 4 summarizes the impact of these three main dynamics on these three different applications.

Table 4 Impacts of the market elements on the technologies.

Legend: (+) positive impact on the diffusion of that technology; (-) negative impact on the diffusion of that technology.

Source: Own elaboration

¹¹ In 1935–1936, GE's profit from incandescent lamps represented 64 to 88 percent of costs, 39 to 47 percent of net sales, and 20 to 30 percent of invested capital. "In fact, the lamp's department of General Electric contributed from one-third to two-thirds of total profit while adding only about one-sixth of total sales." (Rogers, 1980, p.19)

	Efficiency	Role of incumbents	
		R&D	Oligopolistic barrier
CFL	(-) Efficiency was a secondary driver of technological development for the residential lighting market up to the 1990s	(+) Incumbents could sustain long-term R&D projects	(-) CFL and FL experienced oligopolistic barriers that defended the incandescent technology
FL	(+) Efficiency was a main driver of technological development for both the non-residential indoor lighting market and the electronic market		
LED			(+) LED could develop in several markets, thanks to its versatility

The dynamics of lighting histories recall elements of both Mark I and Mark II models. The importance of incumbents in developing long-term energy efficient solutions is a clear Mark II dynamic, in which big players are competitive because they can sustain long-term R&D projects. The important role of new players, especially in the case of fluorescent technology, in diffusing new energy-efficient solutions against the dominance of incandescent technology is a typical example of the Mark I model. The historical combination of these two models was very positive for LED technology and negative for CFL, as the combination of oligopolistic barriers and poor market demand for energy-efficient solutions in residential settings created an environment in which creative destruction occurred very slowly. In contrast, LED technology, which could reap the benefit of the Mark II model incumbents, did not suffer from the absence of more competitive settings in lighting markets.

It is worth remembering, only LED's potential as a general lighting technology was not revealed until the late 1990s, when it became a potential competitor of incandescent technology. In that decade, incandescent technology was weakening under the pressure of increasing demand for more efficient lights, pro-competitive policies, and the diffusion of fluorescent solutions.

Differences in these technologies also point out various roles of policy makers. Only since the 1970s have policy makers promoted efficiency in the lighting sector, efforts that have increased with the new millennium with the push to secure energy supplies and to reduce environmental burdens. Policy makers also have had a relevant role in destroying oligopolistic barriers that slowed the pace of diffusion of fluorescent lights. In the 1940s, anti-trust decisions allowed other firms to break down GE's monopoly. Again, in the 1990s, California launched several initiatives to enhance competition in the CFL market.

The remainder of this section summarizes the four determinants of these technological regimes and identifies three stages in their evolution.

The opportunity (for energy efficiency solutions) dimension

In the first part of the 20th century, energy efficiency was a key driver in the non-residential lighting market, whereas in the residential lighting market, other selective forces, such as light quality and design and fixtures, were more important. In this context, fluorescent tube technology had great value in the non-residential market because of its higher energy efficiency compared with incandescent bulbs. Similarly, in the new electronics market, energy efficiency was a relevant driver of technological development, creating new opportunities for the nascent LED technology. In the residential market, energy efficiency began to drive diffusion of lighting technologies during the 1990s and intensified in subsequent decades, creating a

competitive advantage for CFL, which was superior to incandescent technology in energy performance. In line with these drivers, players in the lighting industry worked to improve CFL technology's energy efficiency, lighting quality, and fixtures design. In the same period, Haitz's law changed the future view of the lighting sector. Consequently, fluorescent technology was no longer considered the long-term solution because LED was expected to outperform it within two decades. This new market forecast influenced firms' strategies and investments as CFL was acknowledged only as a (promising) short- to medium-term solution for phasing out the incandescent market.

The appropriability dimension

At the beginning of the 20th century, a very high appropriability condition characterized the lighting market, resulting in a quasi-monopolistic market structure in both the non-residential and residential segments. In the 1940s, the appropriability monopoly was weakened, and new players and technologies could enter the lighting market. In the non-residential market, where demand was high for new lighting technologies, the fluorescent tube became the dominant solution. In contrast, the weakened appropriability did not stimulate competition in the residential market where demand lagged for fluorescent tubes (and later, CFL). Only when opportunities increased in the 1990s did players become interested in the lighting market, although competition actually started when new pro-competitive policies were approved at the end of the 1990s. Instead, low appropriability conditions characterized LED from the very beginning because the technology could be applied and tested in new markets where dominant regimes and oligopolistic barriers were not yet present. By the 1990s when LED became a lighting solution, the lighting market was already more competitive, and this technology could easily diffuse.

The knowledge dimension

Both the type of knowledge base and the degree of cumulativeness form the knowledge dimension. Incandescent technology was an "easy" technology in the 20th century: The principle of incandescence was widely known and processing methods were quite cheap. Therefore, knowledge about incandescence technology was not a barrier for newcomers. In contrast, fluorescent and LED technologies had a complex knowledge base that required a high degree of cumulativeness. Both technologies are based on novel physical principles (fluorescence and luminescence); therefore, development of these technologies required a new set of capabilities in both research and development and new productive processes. These phases required long-term investments that actually could be sustained only by strong incumbents with sufficient resources to afford the inevitable failures of the R&D process.

The identification of the regimes

These historical findings and our analysis of the determinants of innovation resulted in identification of three main regimes that explain the patterns of development of lighting technologies.

The first regime – up to the 1940s. In this period, high opportunities for energy efficiency solutions in non-residential markets, very high appropriability conditions in the lighting market, and an easy knowledge base for incandescent technology created a context in which GE as the leading player was a front-runner in development of the fluorescent tube. However, for strategic reasons, GE slowed down the process of diffusion

by controlling the lighting value chain in order to maintain a dominant position in the incandescent bulb value chain. Because of the easy knowledge base, control of the value chain was possible only through construction of oligopolistic barriers based on short-term strategies and market power. Meanwhile, residential applications were not investigated because interest in energy efficiency was low in that market segment, and LED technology was being tested first in other novel markets.

The second regime – from the 1940s to the 1990s. Several continuous and discontinuous elements characterized this period: As antitrust policies and expiring patents weakened oligopolistic barriers, new firms entered the non-residential lighting market, and a process of incremental innovation improved the fluorescent technology. In the 1970s, some firms, including GE, started researching fluorescent applications (the CFL) for the residential market as the focus moved to energy efficiency. Meanwhile, the LED was quickly developing in the electronics market, and the first visible LED created an embryonic lighting technology with promising possibilities. At that time, fluorescent technology was considered the lighting technology of the future with the medium-term main market in residential applications.

The third regime – after the 1990s. In the third period, policy makers pressed harder for energy efficiency even in the residential lighting market, and simultaneously, several policies sought to destroy oligopolistic barriers. This combination spurred incremental innovation in fluorescent technology for both residential and non-residential applications. The main drivers of this incremental innovation were lower production costs and improved light quality. As result, fluorescent technology today surpasses incandescent in the residential market because of its greater efficiency and acceptable quality. Meanwhile, Haitz's law deeply changed the future scenario of the lighting market, as LED became the expected new dominant technology and created new opportunities in the long-term. Therefore, firms developed two strategies: i) to substitute incandescent bulbs with CFL bulbs in the short-term period, and ii) to substitute CFL bulbs with LED bulbs in the long-term. Because the knowledge bases for these technologies are cumulative, and CFL knowledge is specialized, some firms with specific semiconductor knowledge focused immediately on the second strategy, trying to shorten as much as possible development of the LED; however, firms with a lighting background focused on exploiting both strategies, although to develop LED technology they had to acquire semiconductor capabilities through an intense process of fusion and acquisitions in the market.

5. Conclusion and lessons for policy makers

In the last century, the lighting industry developed three energy-efficient alternatives to the incandescent light bulb, FL, CFL, and LED. Each technology's history of the development shows different patterns of innovative activities, despite similarities in the determinants of innovation. While FL and LED quickly dominated the market once they were introduced, CFL struggled for decades. More specifically, we observed multiple technological regimes within the same industry, and this paper illustrated how the different technological regimes arose in the lighting industry.

The lighting market was characterized by an oligopolistic Mark II pattern of innovative activity since the beginning of the 20th century when the incandescent bulb was dominant. Typical of an oligopolistic market, the patterns of diffusions of new technologies heavily relied on firms' strategies and market power. The

development of FL and CFL initially took place within this regime, and they were in direct competition with the incandescent bulb. But in the 1950s, the barriers of incandescent technology were weakened by anti-trust rulings, the expiration of relevant patents, and an aggressive market strategy from competitor Sylvania. The increasing importance of energy efficiency played an important role in diffusing these technologies. The non-residential lighting market was already hungry for new energy-efficiency lights, and FL represented the industry's answer. In the mid-20th century, energy efficiency was not a relevant driver of market selection in the residential market; therefore, development of residential energy-efficient solutions was not an industry priority. As result, a weak-learning process plagued CFL technology for decades, broken only with the energy crisis in the 1970s. The turning point was in the 1990s, when policy makers started promoting energy efficiency in the residential market as well. In fact, improving energy efficiency was considered a viable solution to reduce both the demand for new power plants and the environmental burden associated with provision of light. Policy makers perceived the CFL as one of the most effective solutions to quickly control the increase in demand for energy. As result, important incentives helped to diffuse CFL technology, and development accelerated as CFL became attractive for the residential market. Changing attitudes towards energy consumption also pointed out the increasing connection between the environmental question and energy-efficiency dynamics. As illustrated in Section 3, the first fluorescent tubes were not presented as energy-efficiency solutions that could reduce energy consumption, while the CFL had the explicit purpose of reducing energy consumption for lighting.

LED technology followed yet another pattern: initially developing outside the lighting industry as a general-purpose technology that avoided the oligopolistic barriers the fluorescent technology had faced. Initially, LED was not considered a viable competitor to incandescent technology and was able to circumvent the lighting regime to grow stronger in other niches in industries characterized by Mark I patterns. When LED finally matured in the new millennium as a general-purpose lighting technology, the lighting market had experienced important changes. First, policy makers had weakened the oligopolistic barriers, and LED contributed to those changes by allowing semiconductor players to enter the lighting market. Second, energy efficiency had become an important market selection criterion in the residential segment, which made LED a viable substitute. Finally, LED introduced more Mark I elements into the lighting industry but without disrupting the entire industry structure.

In this paper, we showed that fluorescent technologies diffused thanks to the disruption of incandescent barriers. Diffusion was rapid for the fluorescent tube because the market was ready to accept a new technology, but slow for CFL because of market disinterest. In addition, we showed that LED technology is an example of a less disruptive combination of market structure, long- and short-term strategies, and related industries that have changed the technological regime in the lighting industry. More specifically, because of the particular circumstances in which other industries (with other innovative patterns) offered a niche environment for LED to develop, LED was eventually able to bypass CFL as a most promising technology, demonstrating a non-disruptive way to go from Mark II to Mark I. For policymakers, this finding is important because it shows that there are two ways to stimulate new technologies in industries with an undesirable Mark II pattern, opening new policy possibilities.

Article 2. Unveiling scientific communities about sustainability and innovation. A bibliometric journey around sustainable terms

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Abstract

Literature about the relationship between innovation and sustainability has skyrocketed in the last two decades, and new terms that connected these two dimensions have appeared. However, to our knowledge, only one bibliometric analysis reviewed some of these terms (*eco-innovation*, *environmental innovation*, *green innovation*, and *sustainable innovation*) and concluded that they are used interchangeably. These findings were surprising in light of the different position showed in the innovation for sustainability debate and the Kuhnian notion of evolution of scientific knowledge. We proposed a bibliometric analysis based on a methodology that tracks the different meanings and communities associated with these four sustainable terms. Our findings led us to conclude that these sustainable terms cannot be considered interchangeable because they reflect different visions and interests about the relationship between innovation and sustainability. *Eco-innovation* focuses on the development and diffusion of more sustainable products. *Environmental innovation* focuses on the firm level and the relationship between policy and competition. *Green innovation* is the Asiatic approach to environmental innovation. *Sustainable innovation* focuses on transition of complex socio-technical systems and behavioral aspects.

Keywords: eco-innovation; environmental innovation; green innovation; sustainable innovation; bibliometric analysis; Thomas Kuhn

1. Introduction

Thomas Kuhn (1962) highlighted that scientific knowledge about contested topics advances as members of various scientific sub-communities confront differing positions as they explore and affirm their own views on relevant scientific topics (i.e. *paradigms*). In this contraposition, terms and languages have a powerful role because they are used to shape meanings and identify belongings to the different communities (Nicolini, 2012).

The relationship between technology, innovation, and environment is an example of a widely contested topic in which Kuhnian dynamics can be expected to occur. The intensity of the debate depends on the complexity of the topic, as technological change has been considered both the source and the solution for many environmental issues related to anthropogenic activities (Hekkert et al., 2007). The root of academic discovery in this field began in the 1970s, when several authors discussed the feasibility of endless economic growth on a finite planet (Beckerman, 1974; Cole, 1973; Georgesçu-Roegen, 1971; Meadows et al., 1972; Solow, 1973). The well-known idea of sustainable development (SD) was a milestone in this debate. Linking economic growth to the actual state of technology gave innovation a central role, as the way to stretch the limits of economic growth within the availability of finite resources. One consequence of the SD debate was to settle the scientific agenda, with the result that more scholars began analyzing innovation through the lens of sustainability (Freeman, 1996).

Given the importance of this debate and of the language in describing contested positions, we were surprised to find only one bibliometric analysis (Schiederig et al., 2012) that addressed the language dimension of the relationship between innovation and sustainability. The researchers identified four main sustainable innovation terms (*eco-innovation*, *environmental innovation*, *green innovation*, and *sustainable innovation*), and surprisingly concluded that the terms “*can be used largely interchangeably*” (Schiederig et al., 2012, p. 182). This finding provides a non-conflictual view that contrasts with the Kuhnian perspective on the sustainability debate.

For that reason, we performed a different bibliometric analysis that explicitly aimed to disentangle the meanings and communities behind these same four terms. We developed a methodology that combined keywords analyses, as a way to track meanings, with community detection tools based on common references, as way to track communities. Our results confirmed the existence of different meanings and communities, indicating that these terms carry different visions and can be associated with different scientific sub-communities.

Section two briefly introduces the concepts of Kuhnian scientific community and the discourse analysis approach to sustainability. Section three presents the data and methodology used for our bibliometric analysis. Section four presents the main results and discussions, and section five outlines potential future developments for this approach.

2. The Discourse analysis about innovation and sustainability in a Kuhnian world

Before Kuhn, theorists of epistemology and science understood scientists as individual agents free from any social boundaries (Struan, 2006). Royce (1968) was the first to introduce the notion of the scientific community, but Kuhn’s work, *The Structure of Scientific Revolutions* (1962), popularized this topic. In Kuhn’s

view, a scientific community consists of scientists who agree on specific paradigms about reality. Paradigms are ways in which scientists look at the world, and each paradigm consists of specific theoretical frameworks, puzzles to be solved, methodological processes, and potential solutions. Lakatos and Musgrave (1970) called these paradigms the “theoretical hard core” of scientists who shape research programs.

Different scientific communities seek to gain popularity and reproduce themselves as they attract new members through specific processes of education, initiation, and selection in which students have been similarly educated and are thought to use the same language (Struan, 2006). Consequently, paradigms evolve and compete at any time, representing the progress of scientific knowledge. Paradigms and scientific communities are found in all research topics in which different ideologies, approaches, and interests exist.

The use of a common language defines the existence and boundaries of different paradigms and scientific communities. The use of language is a specific subject of study, called *discourse analysis*, which has become popular to address the relationship between science, technology, and society (Hajer and Versteeg, 2005). As Nicolini argued, discourse is “*first and foremost a form of action*” (2012, p. 189) through which each community tries to attach meaning to topics and influence other communities. Consequently, any discourse is a way to sustain specific social group(s) and culture(s) (Gee, 2010). Therefore, discourse analysis can be applied to study the dominant ideologies and values in the scientific world.

Under the lens of discourse analysis, nature and sustainability are socially constructed and historically dependent concepts. As any social concepts, they are widely debated within scientific communities that carry different theoretical lenses, terms, and ideological values (Castro, 2004; Garud & Gehman, 2012; Hopwood et al., 2005; Markard et al., 2012; Pansera, 2012; Rennings, 2000; Scoones, 2007). Consequently, the literature about relationships between innovation and sustainability is expected to follow the same patterns, and to show different terms and values. Thus, the scope of the innovation literature has widened in the last decades to include not only technical innovations (Freeman and Luc, 1997) but also organizational, marketing, institutional, and normative aspects (Fagerberg and Verspagen, 2009).

As a consequence, we could expect to find scholars with different understandings of the four terms that Schiederig et al. investigated. But in fact, we found some cases in which the terms were used interchangeably or as synonyms. For instance, Hellström (2007) used *eco-innovation* as a synonym for “environmentally sustainable innovation.” Accordingly, De Marchi (2012), Oltra et al. (2008) and many others also considered *eco-innovation* as simply an abbreviation for *environmental innovation*, based on Rennings (2000), who also mentioned *green innovation*. Bernauer et al. (2006) also stated, “*The terms eco-innovation and green innovation are used synonymously for environmental innovation*” (p. 3). Andersen (2010) and Pujari (2006) used *green innovation* and *eco-innovation* synonymously, and Halila and Rundquist (2011) used all four sustainable terms to refer to the same concept.

On the other hand, some scholars made explicit distinctions between some of these terms. For example, Foxon and Kemp (2007), Schiederig et al. (2012), Charter and Clark (2007) agreed that an explicit social positive aspect, besides economic and environmental gains, differentiates *sustainable innovation* from the other terms. According to Charter and Clark (2007), “*although the two terms are often used interchangeably, eco-innovation*

only addresses environmental and economic dimensions while sustainable innovation embraces these as well as the broader social and ethical dimensions” (p.10). Also, Ekins (2010) defined *environmental innovation* as “changes that benefit the environment in some way,” while *eco-innovation* is “a sub-class of innovation, the intersection between economic and environmental innovation” (p. 269). In other words, *eco-innovation* is related to both environmental and economic benefits, and *environmental innovation* only to the former.

The complexity of this picture stimulated us to define a methodology to track consistently the existence of different meanings and different communities. This methodology is presented in the next section.

3. Methodology

We reviewed the four sustainable terms (*eco-innovation*, *environmental innovation*, *green innovation*, and *sustainable innovation*) in the literature and applied a combination of content analysis techniques, which draw meanings from the manifest content of language and communication (Baregheh et al., 2009), and community detection in article networks (Blondel et al., 2008). We narrowed the analysis to peer-reviewed, English-written journal articles, gathered through Web of Science (WOS).

We extracted full records for the analyzed articles, including cited references. The keywords at the center of our analysis were the original, author-provided keywords, which exposed a high level of linguistic variation. To prepare these terms for quantitative analysis, we applied a combination of manual consolidation and algorithmic stemming, explained below in more detail. While a certain level of linguistic normalization is essential to achieve comparability, we cannot completely exclude the possibility that changes in meaning structure were introduced in the course of data preparation.

The use of WOS limited the number of analyzed articles, as the number of article records is significantly larger in other bibliographic databases, such as Scopus. However, WOS showed a high level of data curation essential to our analysis. To the best of our knowledge, WOS is the only bibliographic database that normalizes the cited references for each article record across the whole collection. This feature allowed us to calculate pairwise bibliographic coupling and perform the community-level detection, as explained in phase three of the analysis.

We aim to detect: i) potential different meanings carried by the four sustainable terms, and ii) potential different scientific communities behind these terms. Meanings were detected by looking at co-occurrence patterns of keywords. More specifically, we analyzed the co-occurrence between each of the four sustainable terms when used as article keywords and other recurrent keywords. This technique was based on the idea that if a sustainable term is highly connected to specific keywords, these associations may be meaningful. In other words, if these sustainable terms are fully interchangeable, we would not expect to find any specific pattern of correlations because their use would be randomized. To evaluate the association of any keywords with each of the four sustainable terms, we used the term frequency times inverse document frequency (tf.idf) statistic (Rajaraman and Ullman, 2011), which is often used as a weighting approach in information retrieval. The term frequency (TF_{ij}) measures the frequency (number of occurrences) f_{ij} of a term (keyword) i in a document j , normalized by the maximum number of occurrences of any term in the same document:

$$TF_{ij} = \frac{f_{ij}}{\max_k f_{kj}}$$

If the term i is the most frequent term in a document j , then $TF_{ij} = 1$. The inverse document frequency (IDF_i) measures how frequently the term i occurs in a collection of documents, based on the total number of documents (N):

$$IDF_i = \log_2(N/n_i)$$

By combining both the term frequency and the inverse document frequency, we reached the final *tf.idf* equation as follows:

$$tf.idf_{ij} = \frac{f_{ij}}{\max_k f_{kj}} \times \log_2(N/n_i)$$

In our analysis, the “document” was comprised of keywords that appeared together with one of the four sustainable terms. The *tf.idf* counts the number of times a word occurs in a document, discounting for the overall generality of a keyword in the whole corpus. In this way, the importance of keywords (such as innovation) that are fairly general in the overall corpus is lowered, yet they are not excluded from the corpus as contextual stop words. In fact, having a keyword highly associated with all four sustainable terms did not indicate a specific association of the keyword with any of the sustainable terms. Using this relatively simple word co-occurrence, weighting approach, we were able to identify the keywords associated with each of the four terms, and score them by their level of association.

Scientific communities were investigated through an analysis of the articles extracted during the analysis of meanings. For those articles, we investigated: i) the journal in which the paper was published, ii) the authors’ countries of origin, and iii) the cited references.

The analysis was divided into three phases: Phase 1 included the preparation of the database of journal articles. In Phase 2, we analyzed the meanings of the sustainable terms looking at a) the co-occurrences between these sustainable terms used as keywords and other keywords, and b) the content of titles and abstracts of journals articles. Phase 3 consisted of the analysis of the scientific communities, looking at citations, authors, and journals.

Phase 1 – We extracted a list of journal articles from Web of Science that contained the following keywords: eco-innovation, environmental innovation, green innovation, and sustainable innovation. Once the dataset was cleaned, we obtained a list of 241 articles.

Phase 2 – Those 241 journal articles contained 788 unique keywords that were grouped, by stemming or conceptual similarity, by 321 unique keywords for a total of 1,216 hits.

Phase 3 – We investigated the community-level dimension by looking at journals, authors, and citation statistics. To better understand the community structure, we constructed for each of the four terms a network

of strongly associated articles as nodes connected by a bibliographic coupling (BC) measure as edges. BC was computed as:

$$w_{ij} = \frac{n_{ij}}{\sqrt{(n_i \times n_j)}}$$

where n_{ij} is the number of shared references between publications i and j , and n_i and n_j , respectively, the number of references of publication i and publication j for each pair of articles within the term group. We used the Louvain algorithm, which is based on modularity optimization (Blondel et al., 2008), to detect sub-communities in this network. Thus, we could detect clusters of articles that mutually shared many references. A low number of detected sub-communities ideally would indicate a cross-article consistency between use of the four terms and referencing patterns.

Even if the analysis of meanings and scientific communities were done through different phases, we were aware that meanings and communities are not two separate entities. Meanings are carried by communities, which define and shape them. The next section presents the results as separated dimensions, but the discussion includes all results.

4. Results

Our bibliometric analysis found 200 occurrences¹² of the four sustainable terms used as keywords.

Figure 4 Cumulative number of the four sustainable terms used as keywords over time. “Eco” stands for eco-innovation, “Env” for environmental innovation, “Green” for green innovation, and “Sust” for sustainable innovation.

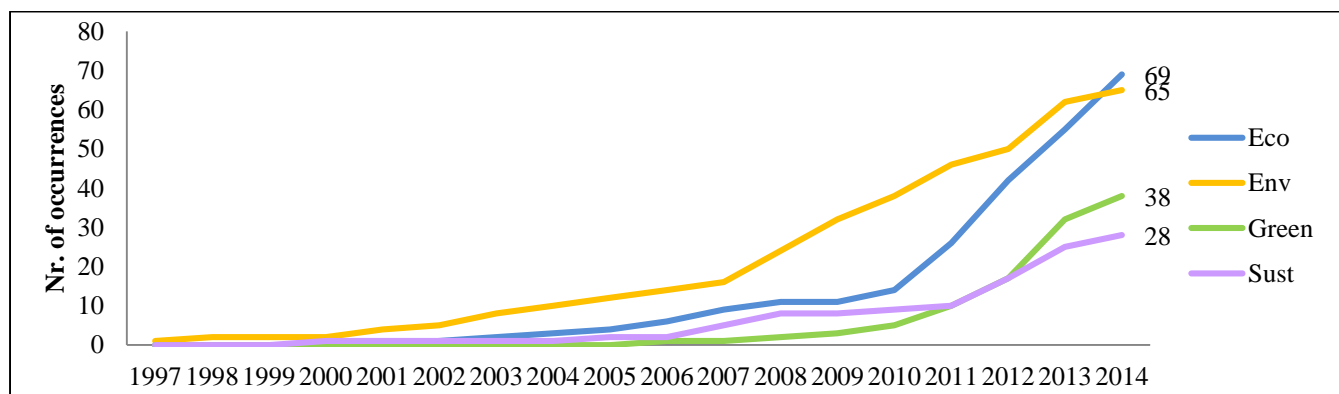


Figure 4 plots the cumulative counts of the four terms over time, indicating that *eco-innovation* and *environmental innovation* were the most popular terms. *Environmental innovation*, which had been used frequently since 2000, was the oldest term, but *eco-innovation* became more popular in the last decade,

¹² Initially, the corpus had 225 records; however, we finally considered only those that contained one of the sustainable terms as author-provided keywords.

especially after 2010. *Green innovation* was a very recent term, and was the most popular in 2013, the last year for which we had full data. *Sustainable innovation* lagged behind in popularity.

Table 5 shows the 20 most important keywords correlated to each of the four sustainable terms.¹³ Keywords were ranked according to the *tf.idf* factor.

Table 5 The 20-most important correlated keywords for each sustainable term. Keywords are ranked according to *tf.idf* value. See the methodology for explanation about the *tf.idf* statistic. Nr. represents the number of occurrences

Environmental innovation			Sustainable innovation			Eco-innovation			Green innovation		
keyword	Nr.	tf.idf	keyword	Nr	TF-IDF	keyword	Nr.	tf.idf	keyword	Nr.	tf.idf
environmental innov	65	0.80	sustainable innov	28	0.77	eco innov	70	0.75	green innov	43	0.79
porter hypothesi	6	0.16	social	5	0.18	ecodesign	13	0.24	green	15	0.31
product	7	0.12	ant	2	0.12	sustainab	14	0.18	corporate	6	0.15
econom	5	0.12	innovation system	3	0.12	triz	6	0.14	environmental manag	7	0.14
voluntari	4	0.12	consum	3	0.12	environmental polici	8	0.12	compet	6	0.14
environmental manag	6	0.11	product/consumpt	2	0.11	product	7	0.11	stakehold	4	0.13
ecological modernis	4	0.11	sustainable business model	2	0.11	indic	4	0.11	environ	7	0.12
polici	5	0.10	product	4	0.11	environ	8	0.11	fuzzy	3	0.10
environmental polici	6	0.10	business model	2	0.10	lca	6	0.10	industri	4	0.10
fuel	4	0.10	entrepr	2	0.10	model	5	0.09	build	3	0.09
technolog	6	0.09	partner	2	0.10	organ	4	0.09	sustainable develop	4	0.08
institut	3	0.09	user	2	0.10	waste	3	0.08	innov	7	0.08
auto	4	0.09	local	2	0.10	technolog	6	0.08	sme	3	0.08
sustainab	6	0.09	sustainable consumpt	2	0.09	energi	4	0.08	taiwan	2	0.08
industri	4	0.09	nich	2	0.08	global	3	0.08	food industri	2	0.07
model	4	0.08	strategi	2	0.08	resourc	3	0.08	environmental sustain	2	0.07
compet	4	0.08	fuel	2	0.07	polici	4	0.07	suppl	2	0.07
innov	8	0.08	sustainab	3	0.07	helix	2	0.07	product	3	0.06
effici	3	0.07	base of the pyramid	1	0.06	innov	8	0.07	manag	2	0.06
patent	3	0.07	client	1	0.06	market	3	0.07	environmental polici	3	0.06

¹³ Data in Table 1 and Figure 1 do not match for *environmental innovation* and *green innovation* because of the process of manual reconciliation mapping. After reconciliation, few articles had twice the same sustainable term. Table 1 indicates the total number of each sustainable term, and Figure 1 the total number of articles.

We found 63 journals that contained at least one article with one of the four sustainable terms. Table 6 shows only the 19 journals with at least two occurrences.

Table 6 Most important journals. “Eco” stands for eco-innovation, “Env” for environmental innovation, “Green” for green Innovation, and “Sust” for sustainable innovation. Probability was calculated as the number of occurrences of a journal on the number of articles in the sustainable term group.

Journal	SUM	Sust		Eco		Green		Env	
		Nr	Prob	Nr	Prob	Nr	Prob	Nr	Prob
J CLEAN PROD (JCP)	42	9	0.32	11	0.16	8	0.21	14	0.22
ECOL ECON (EE)	11	-	-	3	0.04	-	-	8	0.12
BUS STRATEG ENVIRON (BSE)	9	2	0.07	3	0.04	4	0.11	-	-
TECHNOL FORECAST SOC (TFSC)	8	3	0.11	2	0.03	-	-	3	0.05
RES POLICY (RP)	8	-	-	2	0.03	-	-	6	0.09
ENERG POLICY (EP)	4	1	0.04	3	0.04	-	-	-	-
IND INNOV (II)	4	-	-	2	0.03	-	-	2	0.03
J BUS ETHICS (JBE)	4	-	-	-	-	4	0.11	-	-
J ENVIRON ECON MANAG (JEEM)	4	-	-	-	-	-	-	4	0.06
ENVIRON ENG MANAG J (EEMJ)	3	-	-	3	0.04	-	-	-	-
ENVIRON RESOUR ECON (ERE)	3	-	-	-	-	-	-	3	0.05
TECHNOVATION (TECH)	3	-	-	3	0.04	-	-	-	-
INT J TECHNOL MANAGE (IJTM)	2	1	0.04	-	-	-	-	1	0.02
SUSTAIN DEV (SD)	2	-	-	1	0.01	1	0.03	-	-
TOURISM MANAGE (TM)	2	-	-	1	0.01	-	-	1	0.02
DYNA-BILBAO (DB)	2	-	-	2	0.03	-	-	-	-
MANAGE DECIS (MD)	2	-	-	-	-	2	0.05	-	-
QUAL QUANT (QQ)	2	-	-	-	-	2	0.05	-	-
TECHNOL ANAL STRATEG (TAS)	2	-	-	-	-	2	0.05	-	-

Journal of cleaner production (JCP) was by far the most popular journal, and the only one to include all the sustainable terms. Only eight journals (out of 63) had more than one sustainable term.

Table 7 shows the most important countries. counted as the locations of authors.

Table 7 Most important countries. “Eco” stands for eco-innovation, “Env” for environmental innovation, “Green” for green innovation, and “Sust” for sustainable innovation.

Country	SUM	SUST	ENV	GREEN	ECO	COUNT
Germany	26	3	15	-	8	3
Taiwan	24	-	-	16	8	2
England	23	10	3	3	7	4
Spain	23	2	8	2	11	4
USA	21	3	8	5	5	4
France	20	-	11	1	8	3
The Netherlands	18	8	-	1	9	3
Italy	16	-	10	2	4	3

China	9	-	2	6	1	3
Japan	6	-	3	1	2	3
Norway	6	3	2	1	-	3
Canada	5	-	2	1	2	3
Denmark	5	1	-	2	2	3
Australia	5	1	-	4	-	2
Switzerland	5	-	3	-	2	2
Finland	4	1	2	-	1	3
Romania	4	-	1	-	3	2
Sweden	4	1	3	-	-	2
South Korea	3	-	1	1	1	3
Poland	2	1	-	-	1	2
Scotland	2	1	1	-	-	2
Wales	2	-	1	-	1	2
Belgium	2	-	2	-	-	1
Philippines	2	-	-	2	-	1
Portugal	2	2	-	-	-	1
Czech Republic	1	-	-	-	1	1
Greece	1	1	-	-	-	1
India	1	-	-	-	1	1
Luxembourg	1	-	1	-	-	1
Mexico	1	-	1	-	-	1
New Zealand	1	1	-	-	-	1
Slovakia	1	1	-	-	-	1
Turkey	1	-	-	1	-	1

Germany had the most hits. especially for *environmental innovation*. The second, Taiwan, was very focused on *green innovation*. England, Spain, and the United States had occurrences for all keywords. England had a specific focus on *sustainable innovation*. and Spain on *eco-innovation*. France, The Netherlands, and Italy followed with specific specializations. France and Italy, like Germany, focused on environmental innovation, whereas The Netherlands focused on sustainable innovation.

Table 8 shows most cited references.

Table 8 Most cited references. “Eco” stands for eco-innovation, “Env” for environmental innovation, “Green” for green innovation, and “Sust” for sustainable innovation. Probability was calculated as the number of occurrences of a reference on the number of articles in the sustainable term group.

Refs	Nr	Sust		Green		Env		Eco	
		Nr	%	Nr	%	Nr	%	Nr	%
Rennings K, 2000, ECOL ECON, 32, 319	41	-	-	5	0.13	14	0.22	22	0.32
Porter ME, 1995, J ECON PERSPECT, 9, 97	36	-	-	-	-	23	0.35	13	0.19
Brunnermeier SB, 2003, J ENVIRON ECON MANAG, 45, 278	31	-	-	5	0.13	16	0.25	10	0.14

Porter ME, 1995, HARVARD BUS REV, 73, 120	29	-	-	13	0.34	11	0.17	5	0.07
Rehfeld KM, 2007, ECOL ECON, 61, 91	23	-	-	7	0.18	10	0.15	6	0.09
Horbach J, 2008, RES POLICY, 37, 163	22	-	-	-	-	12	0.18	10	0.14
Jaffe AB, 1997, REV ECON STAT, 79, 610	18	-	-	-	-	12	0.18	6	0.09
Chen YS, 2006, J BUS ETHICS, 67, 331	17	-	-	17	0.45	-	-	-	-
Beise M, 2005, ECOL ECON, 52, 5	16	-	-	-	-	6	0.09	10	0.14
Pujari D, 2006, TECHNOVATION, 26, 76	15	-	-	7	0.18	-	-	8	0.12
Hart SL, 1995, ACAD MANAGE REV, 20, 986	14	-	-	14	0.37	-	-	-	-
Carrillo-hermosilla J, 2010, J CLEAN PROD, 18, 1073	12	4	0.14	-	-	-	-	8	0.12
Jaffe AB, 2002, ENVIRON RESOUR ECON, 22, 41	12	-	-	-	-	12	0.18	-	-
Rennings K, 2006, ECOL ECON, 57, 45	12	-	-	-	-	12	0.18	-	-
Pavitt K, 1984, RES POLICY, 13, 343	11	-	-	-	-	7	0.11	4	0.06
Cleff T, 1999, EUROPEAN ENV, 9, 191	10	-	-	-	-	10	0.15	-	-
Shrivastava P, 1995, STRATEGIC MANAGE J, 16, 183	10	-	-	10	0.26	-	-	-	-
Chen YS, 2008, J BUS ETHICS, 81, 531	9	-	-	9	0.24	-	-	-	-
Henriques I, 1999, ACAD MANAGE J, 42, 87	9	-	-	9	0.24	-	-	-	-
Barney J, 1991, J MANAGE, 17, 99	8	-	-	8	0.21	-	-	-	-
Dangelico R, 2010, J BUS ETHICS, 95, 471	8	-	-	8	0.21	-	-	-	-
Eiadat Y, 2008, J WORLD BUS, 43, 131	8	-	-	8	0.21	-	-	-	-
Russo MV, 1997, ACAD MANAGE J, 40, 534	8	-	-	8	0.21	-	-	-	-
Hellstrom T, 2007, SUSTAIN DEV, 15, 148	7	-	-	-	-	-	-	7	.,10
Ashford NA, 1985, HARVARD ENVIRON LAW, 9, 419	7	-	-	-	-	7	0.11	-	-
Fornell C, 1981, J MARKETING RES, 18, 39	7	-	-	7	0.18	-	-	-	-
Fronzel M, 2007, BUSINESS STRATEGY EN, 16, 571	7	-	-	-	-	7	0.11	-	-
Fronzel M, 2008, ECOL ECON, 66, 153	7	-	-	-	-	7	0.11	-	-
Green K, 1994, FUTURES, 26, 1047	7	-	-	-	-	7	0.11	-	-
Lanjouw JO, 1996, RES POLICY, 25, 549	7	-	-	-	-	7	0.11	-	-
Milliman SR, 1989, J ENVIRON ECON MANAG, 17, 247	7	-	-	-	-	7	0.11	-	-
Sharma S, 2000, ACAD MANAGE J, 43, 681	7	-	-	7	0.18	-	-	-	-
Reid A, 2008, ECOINNOVATION FINAL, 0, 0	6	-	-	-	-	-	-	6	0.09
Buyse K, 2003, STRATEGIC MANAGE J, 24, 453	6	-	-	6	0.16	-	-	-	-
Downing PB, 1986, J ENVIRON ECON MANAG, 13, 18	6	-	-	-	-	6	0.09	-	-
Kemp R, 1997, ENV POLICY TECHNICAL, 0, 0	6	-	-	-	-	6	0.09	-	-
Noci G, 1999, R&D MANAGE, 29, 3	6	-	-	6	0.16	-	-	-	-
Nunnally JC, 1978, PSYCHOMETRIC THEORY, 0, 0	6	-	-	6	0.16	-	-	-	-
Chen JL, 2001, J SUSTAINABLE PRODUC, 1, 263	5	-	-	-	-	-	-	5	0.07
De marchi V, 2012, RES POLICY, 41, 614	5	-	-	-	-	-	-	5	0.07
Fussler C, 1996, DRIVING ECOINNOVATIO, 0, 0	5	-	-	-	-	-	-	5	0.07
Mondejar-jimenez J, 2010, ENVIRON ENG MANAG J, 9, 1145	5	-	-	-	-	-	-	5	0.07
Nelson R R, 1982, EVOLUTIONARY THEORY, 0, 0	5	-	-	-	-	-	-	5	0.07
Oecd, 2005, OSL MAN GUID COLL IN, 0, 0	5	-	-	-	-	-	-	5	0.07
Oecd, 2009, EC IND EN GREEN GROW, 0, 0	5	-	-	-	-	-	-	5	0.07
Hekkert MP, 2007, TECHNOL FORECAST SOC, 74, 413	5	5	0.18	-	-	-	-	-	-
Kemp R, 1998, TECHNOL ANAL STRATEG, 10, 175	5	5	0.18	-	-	-	-	-	-
Pujari D, 2003, J BUS RES, 56, 657	5	-	-	5	0.13	-	-	-	-
Coenen L, 2010, J CLEAN PROD, 18, 1149	4	4	0.14	-	-	-	-	-	-
Eisenhardt KM, 1989, ACAD MANAGE REV, 14, 532	4	4	0.14	-	-	-	-	-	-
Elzen B, 2005, TECHNOL FORECAST SOC, 72, 651	4	4	0.14	-	-	-	-	-	-
Evans S, 2004, SOLUTION ORIENTED PA, 0, 0	4	4	0.14	-	-	-	-	-	-
Geels FW, 2008, TECHNOL ANAL STRATEG, 20, 521	4	4	0.14	-	-	-	-	-	-
Shove E, 2003, COMFORT CLEANLINESS, 0, 0	4	4	0.14	-	-	-	-	-	-
Shove E, 2007, ENVIRON PLANN A, 39, 763	4	4	0.14	-	-	-	-	-	-
Bergek A, 2008, RES POLICY, 37, 407	3	3	0.11	-	-	-	-	-	-
Elzen B, 2004, SYSTEM INNOVATION TR, 0, 0	3	3	0.11	-	-	-	-	-	-

Geels FW, 2005, TECHNOLOGICAL TRANSITIONS AND SYSTEM INNOVATIONS: A CO-EVOLUTIONARY AND SOCIO-TECHNICAL ANALYSIS, 0, 1	3	3	0.11	-	-	-	-	-	-
Geels FW, 2010, RES POLICY, 39, 495	3	3	0.11	-	-	-	-	-	-
Giddens A, 1984, CONSTITUTION SOC OUT, 0, 0	3	3	0.11	-	-	-	-	-	-
Larson AL, 2000, BUSINESS STRATEGY EN, 9, 304	3	3	0.11	-	-	-	-	-	-
Lundvall B-E, 1992, NATL SYSTEMS INNOVAT, 0, 0	3	3	0.11	-	-	-	-	-	-
Quist J, 2011, TECHNOL FORECAST SOC, 78, 883	3	3	0.11	-	-	-	-	-	-
Weaver P, 2000, SUSTAINABLE TECHNOLO, 0, 0	3	3	0.11	-	-	-	-	-	-
Yin r K, 2003, CASE STUDY RES DESIG, 0, 0	3	3	0.11	-	-	-	-	-	-

Rennings (2000) was the most frequently cited reference. His work on redefining eco-innovation received wide popularity especially in the *environmental innovation* and *eco-innovation* communities, two terms that he used as synonymous. Porter also was frequently cited, especially for *environmental innovation*, and partially for *eco-innovation*. The *sustainable innovation* references showed a high degree of isolation. Besides Carrillo-Hermosilla, the *sustainable innovation* references were not shared with the other sustainable terms.

Next, we identified sub-communities within the article groups that we associated with the four themes. We identified two sub-communities for *eco-innovation*, four for *environmental innovation*, three for *green innovation*, and two for *sustainable innovation*. The identification of specific sub-communities was used, as starting point of the next section, to discuss the overall dynamics of each sustainable term.

Table 9 The eco-innovation sub-communities

No. Papers	Main Keywords (the name of the theme is the first keyword)	Main authors	Main Localizations	Main Ref Journals	Main References
19	diffusion , economics, policy, growth	Van Wee B; Maat K; Bakker S; Nemoianu EL; Sierczula W	Eurocentric	Ecological Economics, JCP, Res Policy, Tech Forecast Soc	Rennings (2000); OECD (2009); Nelson & Winter (1982); Porter (1995)
11	ecodesign , product development	Chen JL; Bocken NMP	East Asia, Europe	JCP, J Sustainable Produc	Chen (2001); Wenzel (1997); Bocken (2011); Desimone (1997); Lutttropp (2006)

Table 10 The environmental innovation sub-communities

No. Papers	Main Keywords (the name of the theme is the first keyword)	Main authors	Main Localizations	Main Ref Journals	Main References
19	policy , performance, technological change, innovation	Rennings K; De Marchi V; Rammer C; Belis-Bergouignan MC	Eurocentric	J Econ Perspective; Res Policy; Ecol Econ	Porter (1995); Rennings (2000)

16	policy (2), firms, R&D, innovation	Ziegler A; Rennings K; Carrion-Flores CE; Innes R	USA	J Environ Econ Manag; Environ Resour Econ; Res Policy; Ecol Econ	Brunnemeier (2003); Lanjouw (1996);
13	green , performance, management	Huber J; Ziegler A; Junquera B	Germany; Spain; China	Harvard Business Review; Business Strategy; Ecol Econ	Porter (1995); Cleff (1999); Ashford (1985)
11	consumers , emissions, firms, electric vehicles, policy	Kohler J; Brouillat E	Eurocentric	JCP; Res Policy; Technology Analysis and Strategy; Ecol Econ	Malerba (1999; 2007); Janssen (2002); Nelson & Winter (1982); Dosi (1988)

Table 11 The green innovation sub-communities

No. Papers	Main Keywords (the name of the theme is the first keyword)	Main authors	Main Localizations	Main Ref Journals	Main References
12	performance , sustainability, determinants, product development, firm performance	Cuerva MC; Zeng SX; Rotolo D;	Global	JCP; Ecol Econ; Acad Management Journal	Rehfeld (2007); Pujari (2006); Chen (2006); Dangelico (2010); Brunnemeier (2003)
11	performance (2), product development, decision making, supply chain management	Tseng ML; Wu GC; Lu MT	East Asia	J Business Ethics; Acad Management Journal; Harvard Business Review	Chen (2006; 2008); Sharma (2000); Chiou (2011)
12	management , firm, performance, natural environment, strategies	Chen YS; Chang CH;	Taiwan; USA	Acad Manag J; Strategic Management J; Acad Management Review	Porter (1995); Hart (1995); Henriques (1999); Shrivastava (1995)

Table 12 The sustainable innovation sub-communities

No. Papers	Main Keywords (the name of the theme is the first keyword)	Main authors	Main Localizations	Main Ref Journals	Main References
6	tech change , transition, systems, entrepreneurship	Boons F; Quist J;	Eurocentric	Bus Strateg Environ; Sustainable Innovation; Ind Corp Change	Carillo-Hermosilla (2010); Geels (2005); Hekkert (2007)
6	behavior , policy, consumption	Longhurst N; Gabriela L; Rohn H; Tukker A	England	Ecol Econ; Res Policy; J Consum Cult	Shove (2003); Giddens (1984);

5. Discussion

In this section, we address our main question: Are these four sustainable terms interchangeable or do they carry different meanings? We begin with a discussion of the main themes of each sustainable term and the data gathered from keywords, countries, journals, and citations, in order to check the consistency of the various dimensions of the analysis.

The eco-innovation term shows two themes: i) diffusion of environmentally friendly innovations and impacts on growth (diffusion theme) and ii) development of more environmentally friendly products/services (eco-design theme). The diffusion theme was confirmed by the relevant importance of “environmental policy” as a keyword and the reference to the works of Rennings (2000), OECD (2009), and Nelson and Winter (1982), which link a “green growth” strategy to changes in the market and technological dynamics. The importance of structural changes in connection to sustainability was well represented by the importance of journals, such as *Ecological Economics* and *Technological Forecasting and Social Change*. The eco-design theme was characterized by the wide use of product/production related keywords, such as eco-design, TRIZ, life-cycle assessment, and was confirmed by the identification of a specific theme focusing on product development. This theme was specifically found in the *Journal of Sustainable Production*, which focuses on new products/services for sustainability. Rennings’ work was central for that keyword, except for the eco-design theme. Rennings (2000) has contributed to the clarification of the eco-innovation concept in the context of neoclassical and evolutionary economics; therefore, his work highlighted the need to integrate social and institutional changes in innovation study and paved the way for expansion of the eco-innovation research. Meanwhile, the ecodesign-TRIZ-LCA community followed a more technical pattern that focused on improving the environmental performances of the design phase (Chen & Liu, 2001).

The *environmental innovation* term had four themes, two of which were connected to Porter’s work concerning the use of standards to stimulate environmental performance, which results in more competitive processes of production. The policy theme focused on the policy level, and the level of innovation and technological patterns. The green theme was concentrated at the firm level, as highlighted by the use of “management” as a keyword and the publication in *Harvard Business Review* and *Business Strategy*. The *environmental innovation* term had two themes: The policy (2) theme focused on the work of Brunnermeier and Cohen (2003) concerning the determinants of innovation at the industry level. The link between the two dimensions was confirmed by the two main journals (*Journal of Environmental Economics and Management*; *Environmental and Resource Economics*), which connect the firm and the policy/economics levels. The consumers theme focused on sectorial innovation, as indicated by the connection to Malerba, Nelson and Winter, and Dosi, and the importance of the specific keywords “firm” and “electric vehicles.” The connection to Malerba and to Dosi also explained the specialization of Italy as a country for environmental innovation.

The *green innovation* term represents the Asian approach innovation for sustainability. This community was deeply rooted in Taiwan and China, as showed by the consistent number of Asian authors and references, particularly Y. Chen (Chen, 2007; Chen et al., 2006). *Green innovation* focused on a micro-perspective, as indicated by the use of the keywords “corporate,” “management,” and “stakeholders.” The view based on firm performance was also highlighted by the three themes in which performance was the common keyword, but

the others carried the same perspective. Prevalence of journals such as *Academy of Management Journal*, *Journal of Business Ethics*, *Harvard Business Review*, *Strategic Management Journal*, and *Academy of Management Review* confirmed the firm-based perspective of this keyword.

The *sustainable innovation* term was related to the dynamics of consumption and production, as highlighted by the main keywords and the two main themes. The tech change theme was rooted in the transition literature that identified technological changes within broader societal transitions towards sustainability. This view was confirmed by the references to Carillo-Hermosilla, focusing on the need for systemic changes; to Geels and Kemp, who work on the transition and multilevel perspectives; and to Hekkert who studies the technological innovation system. The behavior theme highlighted the behavioral implications of sustainability on consumers and consumption. Overall, with the exception of Carillo-Hermosilla et al. work, the reference analysis indicated that the sustainable innovation literature was separated from the others.

With the main meanings of the four sustainable terms described, we now turn to the contrasts among them. Overall, we found both similarities and differences in the terms. *Eco-innovation* was more product-oriented and focused on developing and diffusing environmentally friendly innovations. *Environmental innovation* and *green innovation* focused more on competitiveness at both the national and firm levels, based on the determinants of innovations.

Environmental innovation was a Eurocentric term, and *green innovation* was widely used in Asia. We believe that the increasing popularity of *green innovation* in the literature may be connected to the increasing importance of the Asiatic scientific community's work on innovation and sustainability. Thus *environmental innovation* and *eco-innovation* showed a similar origin in the works of Rennings and Porter. For that reason, these two communities had several overlaps, consistent with Rennings' initial position, which considered *eco-innovation* an abbreviation of *environmental innovation*. The difference seems to be that within the *eco-innovation* sustainable term, a specific community is focusing on design and life-cycle assessment, and *environmental innovation* is focused more on firm-level performance.

Sustainable innovation followed a more isolated pattern, as indicated from the lack of common references with other sustainable terms. We have highlighted that some scholars think the concept of sustainable innovation includes the social aspect of sustainability. The analysis of the keywords may support that idea, but other differences were apparent. Indeed, *sustainable innovation* focused on transition of complex technological systems and the relationships between production and consumption. The social dimension of sustainability not only refers to the social impacts of innovation, but also includes the role of societal changes in influencing the innovative process. The multi-regime perspective was an important theoretical base in this community, as indicated by the several references to the work of Frank Geels (Geels, 2010, 2005; Geels et al., 2008) and Shove (Shove & Walker, 2007) about the socio-technical approach and transition and to Kemp (Kemp et al., 1998) about regime shifts. The prominence of Geels, Kemp, and Shove highlighted the importance of the United Kingdom and The Netherlands in that literature.

The various communities tended to publish in their own, specific journals, and only *Journal of Cleaner Production* provided a common platform.

6. Conclusion

We reviewed the peer-reviewed literature about the relationship between innovation and sustainability, looking at the different meanings of four sustainable terms: *eco-innovation*, *environmental innovation*, *green innovation*, and *sustainable innovation*. We found that *sustainable innovation* followed an isolated pattern, focusing on transition of complex socio-technical systems and behavioral aspects. The other three sustainable terms showed more commonalities. *Eco-innovation* and *environmental innovation* showed a similar root, but differed in their development, that is, *eco-innovation* was more product-oriented and focused on the diffusion elements and *environmental innovation* was more business-oriented. *Green innovation* seemed to be an Asiatic interpretation of *environmental innovation*.

The Kuhnian perspective was confirmed as a valid key to analyze the evolution of knowledge within the scientific community. Innovation for sustainability can be framed as a complex/contested notion in which different scientific sub-communities highlight different visions and interests. The birth of different terminologies can be explained by the richness of debate among scholars. New and old terms are continuously shaped, abandoned, and re-used to highlight continuity and discontinuity with other meanings and with previous branches of research.

Our research had some limitations that can be removed for further analysis. For example, we focused on the four sustainable terms used by Schiederig et al., but during our analysis, we spotted other terms that may have a specific meaning (and community), such as *eco-efficient innovation*, *low-carbon innovation*, *innovation for sustainability*, *socio-ecological innovation*, and *externality reducing innovation*, among many others. These terms may provide additional knowledge about the evolution of the academic literature and of scientific communities. Moreover, we narrowed the analysis to the scientific peer-reviewed literature. Schiederig et al. proposed an interesting expansion to the Google Scholar literature, but our methodology did not fit that source of data. Therefore, our methodology could be updated to overcome such limitations and provide new insights that go beyond the academic community. For example, do these terms originate with the scientific community and then spread to the general population worldwide, or are any of these terms first framed outside of the scientific community, which then comes to embrace them?

Article nr. 3. Beyond unsustainable eco-innovation: the role of narratives in the evolution of the lighting sector

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Abstract

The discourse of Sustainable Development has reinvigorated the idea that technological innovations are inescapable to sustain economic development and simultaneously achieve environmental sustainability. In this paper, we propose a framework to describe six possible combinations of innovation and demand/consumption levels that constitute in turn six *narratives of sustainability*. We argue that the present global trend is set out for a dominant narrative, what we call 'Green Growth', which is rooted in the idea that economic growth - and thus technological change - is a prerequisite for environmental sustainability. By way of example, we use the case of the lighting industry to show that this narrative cannot assure an absolute reduction of the present levels of energy consumption. We therefore propose to embrace a different narrative of sustainability that encourages at the same time the development of eco-efficient technologies and the reduction of demand/consumption. This alternative narrative is linked to the development of the concept of '*useful light*' and to a paradigm change in which the lighting sector is no longer framed around the electric bulb. This transition would require a new class of Lighting Service Companies (LISCO) and of new functional business models based on the sale of 'useful light'.

Keywords: narratives analysis; eco-innovation; sustainability; green growth; rebound effect; lighting industry; green business models.

1. Introduction

Since the 1970s, the discourse of environmental sustainability has gained a central role in the international public debate and political agendas. From the rise of environmentalism, conservation of the ecosystems and development of the human economies have been seen as two irreconcilable enterprises. Economic growth entailed environmental degradation and environmental conservation constituted an unacceptable constrain for business (Porter & Van Der Linde 1995; Kemp & Andersen 2004).

A number of scholars even questioned the concept of limitless growth of the economic sphere in a planet with finite resources (Boulding 1966; Georgescu-Roegen 1971; Daly 1973; Meadows & Randers 2006). This position was fiercely opposed by those who argued that the limits to growth could be overcome by the endless potential of innovation and technology (Sandbach 1978; Mol & Spaargaren 2000; Bardi 2011). The well-known concept of 'sustainable development' (Brundtland 1987) became an important milestone in the effort to overcome this impasse between economy, technology and environment. Brundtland's report introduced the idea that economic growth is limited by the present state of technology and therefore it is possible to stretch these limits on the condition that technology seamlessly evolves. One of the consequences of Brundtland's perspective was that the discourses of technical change and innovation became hybridised with elements that come from the discourse of sustainability (Freeman 1996). In the after-Brundtland world, a new conceptualisation of innovation based on the idea of eco-efficiency - i.e. the process of minimizing energy, raw material and pollutants per unit of production - gained popularity as a way to integrate environmental and economic goals (Carrillo-hermosilla et al. 2009) among an increasing number of scholars and practitioners (Adams et al. 2012). The eco-efficiency discourse is based on the '*decoupling argument*' i.e. the possibility provided by technological innovations to diminish the amount of materials, energy and waste per unit of GDP (Jackson 2009). Economic growth and environmental sustainability are compatible as long as decouple effects counterbalance the increase in consumption of services and goods. This approach has been stretched up to the idea that economic growth is not only *compatible* with environmental sustainability, but it is also an indispensable *incentive* to it. Only economic growth, indeed, creates the conditions in the market that fuel the development of new greener technologies (Beckerman 1992; World Bank 1992).

Other studies have questioned the eco-efficiency approach to sustainability by highlighting the intrinsic link between economic growth and material consumption (Jackson 2009). For example, the literature focused on the study of the 'rebound effect' demonstrated that the increase of the efficiency of extraction and utilization of natural resources may lead to an increase in their consumption (Birol & Keppler 2000; Alcott 2005; Herring 2006; Polimeni et al. 2008; Saunders & Tsao 2012).

This paper applies the method of Discourse Analysis, which only recently has been operationalized with reference to sustainability and environmental politics (Hajer & Versteeg 2005), to make two major contributions. First, we propose a cognitive map that positions and operationalizes a number of alternative narratives of sustainability and innovation in order to show that the focus on eco-efficiency is only one of the possible interpretations of the relationships between human economies and the surrounding *natural environment*. Second, we apply this map to the evolution of the lighting sector to show how different

narratives may lead to the transformation of the sector by changing the action of the main players in the industry and their business models.

Two conclusions follow. First, the eco-efficiency perspective may ease the purse for environmental sustainability but it is neither needed nor sufficient; therefore demand-side measures are required. Second and consequent, business models that follow the eco-efficiency perspective, like the sale of more efficient lighting bulbs in the lighting sector, may be inadequate to achieve environmental sustainability because they discourage demand-side measures. We therefore suggest an alternative model that we define as *Lighting Service Company* (LISCO) that integrates measures designed to combine eco-efficiency with the reduction of energy consumption.

The article is organised as follows: section one introduces Discourse Analysis and indulges in a brief description of the notion of *frame* and *narrative* to characterize the discourse of sustainability and eco-innovation. The section ends with the introduction of a map that shows how multiple discourses can be debated along two key factors: demand/consumption and innovation. Section two illustrates the case study of the lighting industry focusing on past and current dynamics. Section three analyses the narratives of sustainability of the lighting industry indicating the dominant trajectory, the alternative proposed one, and the frictions that potentially might hamper the transition towards countervailing narratives in the sector. Section four concludes by discussing the limitations of the present work and suggesting future lines of research.

2. The construction of the narratives of sustainability

The study of *language-in-use*, also widely known as Discourse Analysis, has become increasingly popular among those scholars interested in researching the intersection between science, technology, society and politics (Nicolini 2012). More recently, the study of logics and the role of language in environmental politics have gained a relevant position in the Science & Technology Studies (STS) debate (Hajer & Versteeg 2005; Feindt & Oels 2005; Dryzek 2013). This section introduces the notion of discourse, frames, and narrative that, we argue, are crucial to understand the origin and the evolution of the modern concepts of environmental sustainability and eco-innovation.

2.1 Discourse, Frames and Narratives

The word *discourse* in the common language refers to the mundane use of language in social interaction. The word usually describes an articulate discussion or treatment of a subject in the form of speech or writing. At the same time, the term discourse also refers to the ways in which people integrate linguistic and non-linguistic features *'to enact or recognize certain identity [...] give the material world certain meaning, distribute social goods in a certain way, privilege certain symbols systems and ways of knowing over others'* (Gee 2011, p.13). This second meaning has been developed and analysed by several disciplines including linguistics, psychology, politics and history among other social sciences (van Dijk 1985; Gee 2011). The importance of this kind of analysis has gained momentum during the last five decades since an increasing number of *'researchers developed the idea that discourse is, first and foremost, a form of action, a way of making things happen in the world, and not a mere way of representing it'* (Nicolini 2012, p.189). As a form of social practice, discourse

always belongs to social groups, cultures and institutions (van Leeuwen 2008). So when one enacts a specific kind of discursive practice one also sustains specific social group(s), culture(s) and institution(s) (Gee 2011).

The practical implications of discursive practices are evident in the allocation and distribution of social goods, such as sustainability, defined as all the goods (e.g. products, services, values, relationships) that people value. For instance, Hajer & Versteeg (2005) highlight that the discourse analysis applied to environmental politics has contributed to the debate of environmental sustainability adding three crucial dimensions. First, discourse analysis showed that the notion of Nature and Environment is not objective categories but socially constructed and historically situated concepts (Morton 2012). Second, the various discourses of sustainability limit the range of policy options, thus serve '*as precursors of policy outcomes*' (Ibid, p.179). Third, the analysis of discourse provided a solid basis to understand the strategies deployed by powerful actors engaged in environmental disputes to override competing countervailing discourses that potentially might jeopardize their hegemonic positions (Hajer & Versteeg 2011; Stevenson & Dryzek 2012; Hajer & Strengers 2012).

One of the characteristics of the discursive practices is the capacity to create, promote and diffuse cognitive frameworks, mental models that influence action in the real world (van Dijk 1995). In the description of those dynamics the concepts of 'framing' and 'narrative' occupy a relevant position. The process of framing is a process of simplification of reality (Goffman, 1986 [1974]p. 40-45) carried by specific actors and shaped by their particular institutional, political and life settings (Carragee & Roefs 2004). The interpretation of reality always follows a specific logic (Tannen 1993) and includes subjective and values judgements (Entman 1993; Leach et al. 2010). According to Entman (1993), the interpretative process takes place in four steps: frames 'define problems' (i.e. define who or what is doing what, who is damaged or benefited, usually measured in terms of social goods or cultural values), 'diagnose causes' (i.e. identify the source(s) of the problem), 'make moral judgements' (i.e. define what is 'just' to do and what is not) and 'suggest remedies' (i.e. propose action). Frames highlight some aspects of reality whilst obscuring other elements. Frames are represented by narratives that are 'simple' stories that start defining a problem, elaborate their consequences and ends by outlining solutions (Roe 1994). Since narratives represent frames, they imply a number of practices that involve value judgements about what or who is excluded and included and what issues, questions and solutions are prioritized.

2.2 The discourses of environmental sustainability and eco-innovation

As Hajer & Versteeg (2005) suggest, Discourse Analysis can be fruitfully applied to the study of environmental politics. Furthermore, we suggest that, such an analysis can provide useful insights to analyse the interaction between the discourse of technological innovation, and that of environmental sustainability. One of the reasons that justify such an enterprise is the recent hybridization of the discourse of technological modernization with elements that originated within the discourse of environmental sustainability. An emblematic example is the increasing popularity of adjectives as 'eco', 'environmental', 'green' or 'sustainable' in connection with innovation (Rennings 2000; Hellström 2007; Pansera 2012; Schiederig et al. 2012). This trend has intersected with natural science and engineering (Hueting & Reijnders 1998), innovation studies (Freeman 1996), and entrepreneurship studies (Porter & Van Der Linde 1995).

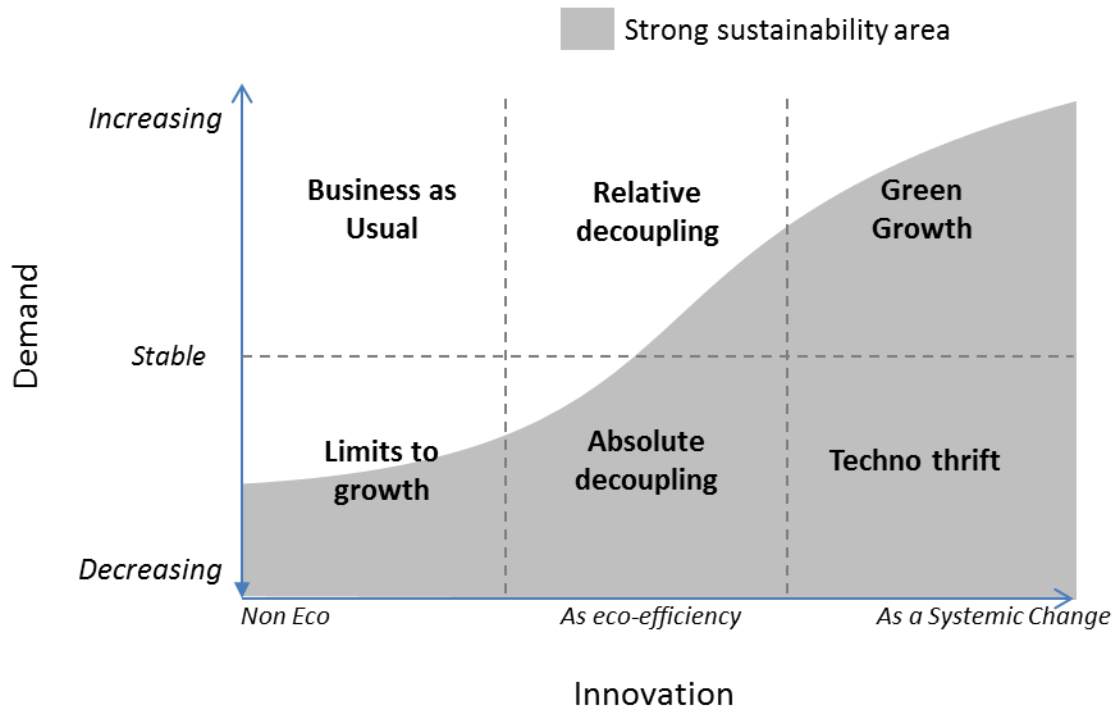
The practical outcome of this process of hybridization of sustainability and innovation is a formulation of eco-innovation articulated in three levels (Carrillo-hermosilla et al. 2009; 2010): (i) add-on and/or end of pipe solutions i.e. incremental improvements of pre-existing technologies that reduce the environmental impact; (ii) sub-system changes i.e. eco-efficiency improvements operated within well-established technological paradigms (paradigm meant as in Dosi (1982)) ; (iii) Eco-effectiveness or systemic changes i.e. new technological paradigms that lead to drastic eco-efficiency leaps i.e. closed-loop systems and cradle-to-cradle design.

Despite the sophistication achieved by the discourse of eco-innovation, in the realm of practices the concept remains often framed in terms of mere eco-efficiency (Hellström 2007; Jänicke 2008; Pansera 2012). This is because, we argue, the notion of sustainability on which the discourse of eco-innovation is rooted is still the contested field of competing frames (Castro 2004; Hopwood et al. 2005; Scoones 2007). Here, for simplicity, we distinguish between two major conceptual framings within the broader discourse of environmental sustainability: *weak* and *strong* sustainability. Weak sustainability considers human and natural capitals as inter-changeable. An economy is *weakly* sustainable '*if the ratio of savings to income (which allows investment) is larger than the sum of the ratios of depreciation of human-made capital and "natural capital"*' (Martinez-Alier 1995). On the contrary, strong sustainability implies the conservation of a critical natural capital e.g. wet land, fishery stocks, and forests (Costanza & Daly 1987; Daly 1987; Daly & Farley 2007). These two framings lead to at least two relevant questions about sustainability: *To what extent is it possible to improve the efficiency of the conversion of natural capital into human-made capital? Is it reasonable after all to consider natural and human-made capital interchangeable?*

Following these questions, we argue that the present discourses of innovation as a way to address the environmental issues produced by industrialization (i.e. the discourse of ecological modernization (Jänicke 2008)) are mainly framed within two major positions: one is based on the idea that innovation, framed especially as eco-efficiency, can create the conditions that allow both economic growth and the conservation of the natural environment; the other is based on the idea that to achieve environmental sustainability, measures to control the demand are needed.

In order to analyse the dynamics and the potential evolution of the discourses of sustainability and innovation along the two conceptual keys of innovation and demand/consumption, we propose a framework (see figure 1) to identify six possible narratives that are explained in the next section.

Figure 5 six narratives, and six pathways



3. Six narratives, six pathways

In Figure 1 we plot the dynamics of innovation vis-à-vis the evolution of demand. In the chart innovation can assume essentially three forms: a *non-eco* form in which eco-efficiency is not contemplated, on the contrary, it might even decrease; an *eco-efficiency* form in which innovation decouples economic growth from the consumption of non-renewable resources through technological progress; finally a *systemic* form in which innovation promotes changes in institutions, culture and society in order to create positive feedback between the development of greener technologies and the conservation of non-renewable resources. These three forms of innovation are combined with an *increasing* or *decreasing* demand.

The result is a space composed by six areas, six interpretations of the relationship between innovation and demand that, following the notions introduced in section 2.1, we could define as *narratives* (see Table 1). The area in grey in the graph represents the 'strong sustainability' zone where natural capital can be preserved in its absolute value by reducing its depletion and/or increasing the efficiency of its exploitation. On the contrary, the white area coincides with the 'weak sustainability' zone where human-made capital is considered a legitimate substitute of natural capital.

Table 13 Frames underlying the six narratives

	Define problems	Diagnose causes	Moral Judgments	Suggest remedies
Business As	Low consumption	Low economic	More consumption is	Foster innovation to feed economic

Usual	hampers well-being	growth	always better	growth
Limits to growth	Demand collapses	Depletion of not renewable resources	The Planet is finite	Authoritarian governance/voluntary frugality
Relative decoupling	Increasing demand of non-renewable resource hampers future growth	Low eco-efficiency improvements	Priority of economy over the environment.	Foster eco-efficiency
Absolute decoupling	Increasing demand of non-renewable resource threat ecosystems balance	Consumption and efficiency are addressed separately	Priority of the environment over economy.	Foster eco-efficiency and at the same time control demand
Green growth	Consumption and economic growth do not decouple quickly enough	Markets do not prioritize green technology	The richer we are, the greener we are	Economic growth is a prerequisite for sustainability i.e. increase demand for green technologies to increase economic growth and vice versa
Techno-thrift	Demand decrease do not necessarily lead to well-being	Green technologies are not fully exploited through systemic changes	A thrifty society is more likely to produce sustainable technologies and vice versa	Foster systemic change in both culture and technology

3.1 From non-eco innovation to green growth

The business-as-usual narrative refers to the pre-environmentalism paradigm in which economic growth (and therefore consumption growth) is a priority, and environmental sustainability is not explicitly considered. In this case, innovation is not supposed 'to be green'. This narrative finds its legitimation in the frame of weak sustainability: as long as natural capital is converted efficiently into human-made capital, the system is considered to be sustainable. At the same time, the amount of human-made capital is supposed to increase at the expenses of natural capital (Arrow et al. 2004).

By introducing the concept of strong sustainability, this narrative can evolve through two sequential stages. In the first (i.e. from *Business as usual* to *Relative decoupling*), natural and human-made capitals are no longer considered interchangeable. As natural capital must be preserved, economic growth can continue only through an increment of eco-efficiency. Economic growth becomes compatible with environmental sustainability only when it is decoupled from resource consumption (Hammer et al. 2011).

In the second passage (i.e. from *Relative decoupling* to *Green growth*), economic growth and environmental sustainability are not only potentially compatible, but they have mutual positive feedback (Grossman & Krueger 1991). In this view, as Kuznet's followers theorised, economic development is a prerequisite *to become green* (Martinez-Alier 1995). On the one hand, economic growth is a prerequisite because higher demand encourages the development of greener technologies (Beckerman 1992). On the other hand, environmental sustainability becomes an opportunity to create economic growth. We call this narrative as Green growth narrative. In the Green growth narrative, environmental innovation is seen as a win-win solution (Ambec & Lanoie 2008), because any innovation that increases eco-efficiency has a positive impact on economic growth, and economic growth has a positive impact on the preservation of natural capital.

The strong sustainability of these narratives depends on the capacity of having a process of decoupling quicker than the pace of growth of economy (Shafik 1994). This dynamic can be stretched to the limits of the extreme case of 'zero impact eco-innovation' (Deloitte 2012; Schiederig et al. 2012), in which economic growth is no longer supported by material consumption, the so-called *dematerialised economy* (Daly 1987; Roy 2000). This is the consequence of the scenario depicted by the Nobel laureate R. Solow in his harsh critic to Meadows' work in the 70s (Solow, 1974). Such a scenario would imply major systemic changes not only in the technological sphere but also in the way production and consumption are organised (Raskin 2008; Leach et al. 2012).

Nowadays, this narrative has a strong appealing because it addresses at the same time and with mutual benefits both economic crisis and environmental issues. Therefore it has been enthusiastically embraced by many scholars (Fussler & James 1996; Klemmer Lehr & Lobbe 1999; Keeble et al. 2005; Chen et al. 2006; Kemp & Pearson 2007; Oltra & Saint Jean 2009) and several influential actors, i.e. the OECD (OECD 2010; Hammer et al. 2011; OECD 2011), the International Energy Agency (Pasquier & Saussay 2012), the US Government (Doris et al. 2009), the European Union (European Commission 2011b; European Commission 2012), and the World Business Council for Sustainable Development (WBCSD 2000), among many others.

3.2 From collapse to techno-thrift

The three narratives exposed above have been the targets of several criticisms (Hopwood et al. 2005). Even if eco-efficiency is acknowledged as a fundamental driver of innovation (Nordhaus 1998), many scholars question the feasibility of an endless economic growth within the physical limits of our planet (Georgescu-Roegen 1975; Leach et al. 2012). Others argue that the tendency to associate eco-efficiency with eco-innovation is not sufficient to tackle complex environmental problems like climate change and biodiversity disappearance (Jänicke 2008). Although efficiency has steadily grown during the last centuries, few people would argue that the planet is not facing several simultaneous environmental crises (Rockström et al. 2009).

In an effort to overcome the shortcomings of eco-efficiency, the concept of eco-effectiveness has been introduced (Carrillo-hermosilla et al. 2010). Eco-effectiveness includes those eco-innovations that deliver cultural and/or technological systemic changes that are able to trigger an overall reduction of the consumption of natural resources. Those changes encompass producers and users, their behaviours, their technological horizons and the complex reality of the surrounding natural world.

The study of the rebound effects represents the first systemic attempt to unveil very accurately the contradictory relation between eco-efficiency and consumption (Herring & Roy 2007). Jevons was the first to realize in 1865 that an increasing efficient consumption of coal was leading to an increasing consumption of it. The rebound effects (also known as Jevons or N-Curve effect) imply that the gains in efficiency produced by technological innovation can be minimized or even neutralized by an increasing demand (Saunders 1992; Alcott 2005; Polimeni et al. 2008). Commonly, rebound effects have been described as behavioural responses to technical improvements (Sorrell 2007). For example, Tainter (2011) shows that, as vehicles with higher fuel economy entered the U.S. fleet from the late 1970s onwards, Americans responded by driving more. Similar conclusions are provided by other authors in several sectors (Newman & Kenworthy 2006; Herring 2006; Sorrell 2007; Tsao & Waide 2010; Saunders & Tsao 2012). However, the real magnitude of rebound effects is quite hard to calculate due to the complexity of the systems in which they occur and the time dimension being considered. Furthermore the relations between innovation and consumption underlie overarching elements that cross the realm of technology. For example, relying on eco-efficiency solutions might lower the psychological commitment towards sustainable behaviours (Lorenzoni et al. 2007; Peters et al. 2012; Soland 2013).

At the same time, the critique of the Green growth narrative comes also from those who question the very concept of economic development (Schumacher 1973; Illich 1973; Hirsch 1977; Escobar 2000) and those who criticize the concept of economic growth (Fournier 2008; Martinez-Alier 2009; Kallis 2011). According to these authors, environmental sustainability can be achieved only through a shift of paradigm from a consumerist society to a steady-state economy (Daly & Farley 2007) or to a de-growth society (Kallis 2011).

Despite the differences between those approaches, these critics share an important conceptual point: in the long term, environmental sustainability implies an obligated limitation (or decrease) of demand/consumption. This limitation may or may *not* be accompanied by a technological push framed in terms of eco-efficiency. We call *Limit-to-growth* narrative the case in which a reduction in demand is not supported by an increase in eco-efficiency. In this case, the patterns of consumption encounter the natural limits of the planet and the demand/consumption levels inevitably shrink or eventually collapse (Meadows & Randers 2006). This scenario can have either pleasant or unpleasant consequences. The pleasant case occurs if societies develop a keener attitude towards frugality and the awareness about the ecological limits in which humanity lives. The unpleasant one occurs when the encounter with the limits happens in societies that encourage consumption. This could be the case of economic recession where people suffer a rapid impoverishment or the case of *fortress-world*, an eco-fascist scenario in which an elite in its ivory tower decides *who can consume what* in order to deal with increasing resource scarcity (Raskin 2008; Bonaiuti 2012). Even if this scenario might potentially assure strong sustainability, it posits controversial moral issues.

The introduction of the eco-efficiency perspective moves the discourse towards the *Absolute decoupling* narrative. In this narrative, economic growth is not excluded as long as a pattern of reduction in the use of non-renewable resources is assured. This scenario creates a hierarchy in which environmental sustainability is prioritized over economic growth. This is what Raskin (2008) has called 'Conventional Worlds' pathways i.e. a number of cultural changes that would combine eco-efficiency with a voluntary reduction of personal

consumption encouraged by a set of political reforms aimed at reducing absolute material consumption at macro-scale.

The last narrative, which we call *Technological thrift*, implies a scenario in which frugality and new green technologies go hand in hand. In the Green growth narrative, economic growth was the indispensable incentive to sustainability; here, frugality and parsimony are the indispensable incentives to it, because they forge the technological progress towards a clear sustainable commitment. This transition implies very deep changes in the way consumption and technology are perceived and performed, and it would include the deployment of a strong sustainability strategy accompanied by a paradigmatic shift in consumption behaviour.

This narrative may be fruitfully understood by combining the already mentioned keener attitude towards frugality at the consumption-innovation dynamics deepened by applying various systemic approaches that are nowadays very popular (Lundvall 2007; Godin 2007; Markard et al. 2012). Markard et al. (2012) have recently overviewed the 'sustainable transition' literature identifying, as in the case of the eco-innovation literature, a huge variety of terminology. They spot several research approaches that point to understand the complex mesh of relations between innovation, transition and sustainability. At the very core of all these perspectives, there is the idea that sustainability requires major societal transformations, not only in policies and technologies, but in practices and business models as well. As a consequence, the impact of innovation depends on the diffusion and consumption dynamics that occur among stakeholders (Geels 2002; 2011; Penna & Geels 2012).

The next section reports the main technological achievements and the market dynamics of the lighting industry. The case is thought to show how the eco-efficiency notion influenced the construction of sustainability narratives in the sectors and is the base for a discussion about future possible alternatives.

4. The evolution of the lighting industry

The lighting case is a remarkable example of a sector that has witnessed a tremendous increase in energy efficiency and, at the same time, a boom of energy consumption. It represents an extreme case that can provide useful insights to understand how the narratives exposed in the previous sections evolve. Extreme cases like this are potentially useful to formulate generalization that can be extended to other sectors (Flyvbjerg 2006).

The history of the artificial lighting began with the use of the open fire as the first artificial light source about 1.4 Ma ago. However, only in the last century, which marks the dawn of era of electricity, three major lighting technological breakthroughs occurred: (i) the incandescent lamp (e.g. Edison and Tungsten light bulbs) at the beginning of the 20th century; (ii) the fluorescent lamp during the 20th century; and (iii) the light emitting diode (LED) technology today (and tomorrow). Looking retrospectively at the whole history, the efficiency of lighting technology has made several remarkable leaps forward (Krames et al., 2007) (see

).

Table 14 Efficiency of lighting technologies. Light efficiency is measured in lumens/W. Lumen is the standard unit of visible light emitted by a lighting source. The lumen/W measures the light emitted per unit of power. Source: own elaboration on Bright (1949), Nordhaus (1998), Coltrin et al. (2008), Pimputkar et al. (2009) and Navigant Consulting Inc. (2012b).

Device	Year	Lumens/W***
Open fire	1.4 million B.C.	0.002
Neolithic lamp	10.000 B.C.	0.015
Candle	1800	0.075
Oil Lamp	1815	0.134
Town gas lamp	1827	0.130
Kerosene lamp	1855	0.049
Edison lamp	1883	2.600
Tungsten lamp	1920	11
Fluorescent tubes ¹	1947	30
CFL	1992	68
LED Lamp	2010	97-135
LED Lamp	2020	224-235
LED theoretical max	-	260-408
Maximum theoretical lighting efficiency	-	683

The last century shows the most amazing increase in energy efficiency. The tungsten lamp increased energy efficiency by 90-folds compared with the oil and gas lamps. The fluorescent tube and the CLF increased efficiency by 5-7 times in comparison with the tungsten lamp (Bright 1949; Bright & Maclaurin 1943), and the LED is expected to be 1,500 times more efficient than the gas lamp.

Every new lighting technology quickly diffused in the market. The incandescent bulb was introduced at the beginning of the 20th century and, by the 1930s, it had conquered nearly 75% of the market share (Bright & Maclaurin 1943; Fouquet & Pearson 2006).

The fluorescent tube was introduced in the New York World Fair in 1939. Only 200,000 fluorescent lamps had been sold in 1938 but, after the fair, the number increased to 79,100,000 in 1947. The fluorescent tubes became the dominant technology in the non-residential market already in the 1950s (Smithsonian Institution 2013). From the oil crisis in the 1970s, the lighting industry started working on the development of fluorescent tubes for residential applications, but the residential market only started to grow only at the beginning of the 21st century (Weiss et al. 2008). Table 15 reports the market share and average efficiency of the lighting technologies available in the 19th and 20th centuries.

Table 15 Evolution of lighting technologies in the UK. Efficiency is calculated in lumen-hours per kWh. Source (Fouquet & Pearson 2006)

Year	Candles		Whale oil		Gas		Kerosene		Electricity	
	Share	Eff.	Share	Eff.	Share	Eff.	Share	Eff.	Share	Eff.
1700	99%	28	1%	20						
1800	90%	37	10%	56						
1900	1%	80			82%	497	15%	246	2%	1,310
1950					1%	887			99%	11,660
2000									100%	25,000

Nordhaus (1998) calculated that such technological revolutions produced a drop in the price of artificial light of 99.75% over two centuries. To the date, the energy efficiency of lighting technology is still steadily increasing. For instance, in the last decade, the average efficiency of the U.S. lighting market rose by 30% from 45 lm/W in 2001 to 58 lm/W in 2010 (Navigant Consulting Inc. 2012c). Today, the incandescent technology represents half of the installed bulbs, but only one quarter of energy consumption and only 8% of the artificial light are produced every year (ibid.).

This historical trends show that energy efficiency undoubtedly has been one of the major drivers of innovation and one of the strongest incentives to the expansion of the market. Lighting worldwide accounts today for 2,600 TWh, which is roughly 19% of world electricity consumption and it is directly responsible for the emission of 1,900 million tons of CO₂ in 2006 (European Commission 2011b). Those data are remarkable but also paradoxical: the energy efficiency of lighting technology has tremendously increased but so had the energy consumption for lighting. In order to understand this dynamic, it is important to look at the patterns of consumption in the lighting sector and compare them with the patterns of efficiency increase.

Since the very beginning of lighting industry, several analysts acknowledged that the introduction of incandescent bulbs was actually increasing the demand for lighting (Nye 1992). For instance, Bright noticed that *'where once 5 or 10 foot-candles were deemed adequate, from 50 to 75 foot-candles are not now considered excessive'* (1949, p.4). According to the same author, in 1939 31 billion kilowatt-hours was consumed for electric lighting and almost one-fourth of public utilities investments were allocated to the provision of electricity for lighting (Ibid.).

The increasing use of the incandescent bulb created the conditions to investigate new and more efficient lighting technologies. Inman (1939) indicated three main issues related to the diffusion of the incandescent

lamp that fostered the research for new more efficient lighting technologies: (i) cost of electricity bill; (ii) wiring overload; (iii) uncomfortable increasing indoor temperature because excessive heating dissipation from the incandescent filament.

Again, as for the diffusion of the incandescent technology, the net effect of the new fluorescent technology was to increase the total consumption of lighting and the number of the installed bulbs (Bright & Maclaurin 1943). Several studies have recently investigated the overall dynamics of energy consumption for lighting. For instance, Fouquet and Pearson (2006) report an increase of total lighting consumption, expressed in lumens-hours, by 1,2700,000 times and pre-capita by 6,500 times in the last three centuries. Tsao et al. (2010) have analyzed lighting consumption patterns over the last three hundred years in six continents founding that *'the result of increases in luminous efficacy has been an increase in demand for energy used for lighting that nearly exactly offsets the efficiency gains — essentially a 100% rebound in energy use'* because *'there is a massive potential for growth in the consumption of light if new lighting technologies are developed with higher luminous efficacies and lower cost of light'* (Ibid.:15). They report that expenditure for lighting has constantly represented the 0.72% of the GDP over the last three hundred years, irrespective of the efficiency of the technologies in use. Similar considerations about the persistence of rebound effects in the lighting sector have been reported by Birol and Keppler (2000) and Herring (2006).

5. Framing sustainability in the lighting sector

We show that the lighting sector is in the middle of a *narrative transition* from a *Business-as-usual* narrative to a Green growth narrative. This happens because society has increasing concerns about sustainability and, as a result of the rebound effects, the energy demand for lighting did not show sign of decreasing. At the same time, we show that the practices that a Green growth narrative inspires cannot assure an absolute reduction of energy consumption. As an alternative, we use the framework introduced above to propose a new pathway based on a number of systemic changes in which efficiency and demand measures are jointly considered. This alternative pathway should imply the development of new business models that are consistent with the absolute decoupling/technological thrift narratives, reframing how technologies and practices are perceived in the lighting sector.

Before moving on, we would like to stress that our considerations focus only on energy efficiency in lighting industry and intentionally exclude other eco-efficiency dimensions (e.g. raw materials, energy consumed, and pollutants produced through the whole life-cycle) as well as other sustainable-related dimensions (e.g. losses of biodiversity due to lighting pollution, health effects on circadian human systems, impacts of heating for lighting on energy loads for cooling/heating systems) that would add more complexity to the analysis. In addition, we do not take in account the opportunity, external to the lighting sector, of enlarging the area of strong sustainability by increasing the use of renewable sources in the production of electricity. Given such simplifications, we acknowledge that this exercise represents a theoretical/conceptual contribution, more than an operational one, to understand the potential impacts of narratives construction in shaping relations between innovations and sustainability in the lighting sector.

5.1 A dominant narrative: the tale of green growth

As we have seen above, the Green growth narrative preaches the stretching of the extant technological paradigms to revamp economic growth in a new environmentally sustainable fashion. In this quest, eco-innovation as framed in a market economy plays a central role. The frame of the green growth can be shortly presented in four steps:

- *Defining problem:* In all the advanced economies economic growth is slowing down. The sustainability of economic growth in the long term is at risk.
- *Diagnosing causes:* The slow pace of eco-technological improvements cannot tackle environmental degradation and limits further economic growth.
- *Making moral judgments:* The richer we are, the greener we are. Economic growth is crucial for human well-being because it opens new possibilities. More consumption is always better.
- *Propose remedies:* Since the development of green technologies requires economic growth and vice versa, a strong commitment in fostering the ecological modernization of all the present technological paradigms is needed.

The Green growth narrative is dominant within the discourse of the three most influential lighting players i.e. Philips, Osram and General Electric (Bryant 2012). From their public discourses, it emerges that these companies expect the LED to become the future of green lighting technology, opening new opportunities for the market. General Electric, for instance, labelled its main lighting program 'ecomagination'. The initiative aims at achieving innovative solutions to tackle the 'present environmental challenges and foster growth'. OSRAM indicates that it is possible to do more with less thanks to efficiency improvements (Sylvania 2009). Similarly Philips expects that improving efficiency is a key driver of sustainability (FrostLighting Supply 2010; Philips 2013). According to Philips, LED opens tremendous opportunities for new applications and solutions (Provoost 2009).

These companies see a positive relation between economic growth and sustainability thanks to the development of the LED technology: increasing demand of light will create new opportunities for developing more efficient lighting technologies and, vice versa, new efficient lighting technologies will create new demand for lighting. A similar approach is shared by scholars (Kemp & Pearson 2007), policy makers (Machiba 2010; OECD 2011; European Commission 2011a; 2012; Navigant Consulting Inc. 2012a; 2012b; UN 2012), and research players (COWI 2009; Wuppertal Institut 2009).

The Green growth narrative in the sector finds its environmental legitimation in the tremendous increase of efficiency that occurred through the history and, above all, from the expectation of future fabulous efficiency performances created around the LED technology. Energy efficiency of lighting is today 1,000 times higher than in the 18th century, 500 folds higher than in the 19th century and 5 folds higher than in the first half of the 20th century. The LED is expected to push further the efficiency performance of lighting devices. The 'Haitz's law' (Haitz et al. 1999) indicated that LED technology will show a cost reduction by a factor of 10 per decade and an

increase of lighting output per LED by a factor of 20 per decade. It is today estimated that LED efficiency will grow up to 224-235 lm per Watt (W) in 2020 (Navigant Consulting Inc. 2012b) with a maximum cap of 260-408 lm per W (Coltrin et al. 2008; Pimputkar et al. 2009). By 2020 energy efficiency of LED bulbs is expected to be 15 times higher than the incandescent ones and 4-6 times higher than the fluorescent ones, with a theoretical limit of 683 lm per W. By 2015 the standard price for LED solutions is expected to be competitive with the other pre-existing technologies. By 2030 the LED is expected to achieve 73% of the market share (Navigant Consulting Inc. 2012c). This trend is supported by several studies (for an exhaustive review see (Tsao et al. 2010)).

One of the reasons that moved the dominant actors in the industry to embrace a Green growth narrative can be found in the traditional business model adopted in the sector that rewards the sale of more efficient lighting bulbs in two ways. First, new efficient bulbs artificially reduce the life cycle of the old ones, because consumers may be tempted to change the old bulbs, even if working, to reduce the energy bill. Second, new efficient bulbs can be sold at higher price because of their potentiality of saving energy. Therefore, the development of ever increasing efficient bulbs is a priority for the economic sustainability of the lighting sector, as already observed in the case of the fluorescent tube (Bright 1949) and of the compact fluorescent lamp (U.S. DOE 2006). Consequently, the lighting players have started support actions that focus on increasing the efficiency performance of lighting bulbs (e.g. the EU ban on incandescent bulb) as a way to pursue sustainability and create a new market for more efficient lighting bulbs. LED technology is claimed to be able to save 75% of the energy currently consumed in the sector (Navigant Consulting Inc., 2012). For this reason, in the lighting industry the LED is widely framed, by the green growth advocates, as the greenest technology ever (Haitz et al. 1999).

The players within the industry may discourage actions designed to reduce energy consumption because such measures have a negative impact on their traditional business models for two reasons: i) energy conservation measures reduce the value of more efficient electric bulb because it lowers the potential of energy savings by shifting towards more efficient solutions; and ii) energy conservation may prolong the lifecycle of the current installed bulbs.

Nevertheless, despite the enthusiasm of the lighting industry, the LED is expected to increase the energy efficiency of lighting by 4 times; a modest advance if compared with the increase of 1,000 times achieved in the last century. These figures suggest that the efficiency of the lighting technology is approaching a sort of technological/physical limit. Reaching such limit may become a relevant problem, because there are no clear signs of saturation on the demand side that may assure that such advance in efficiency will decrease energy consumption for lighting. Tsao et al. (2010) foresee that the consumption of energy for lightning is likely to decuplicate in the next decade, a scenario that would offset any improvement delivered by the LED. Similarly,

an analysis carried out by McKinsey&Co (2011) suggests that 6 out of 7 projected megatrends of the lighting market will be characterized by an increase in lighting demand¹⁴.

Consequently, we argue that the widespread diffusion of the LED technology within the dominant Green growth narrative is likely to further improve the energy efficiency of lighting technology but those improvements might not be sufficient to reduce the energy consumption for lighting. We argue that, in order to reduce energy consumption for lightning in absolute value, the sector should integrate the development of highly efficient technology like the LED with measures that aim at reducing the demand. Inevitably, such a change implies a reframing of the Green growth narrative.

5.2 Exploring alternative narratives: from bulbs to lightness

The need to develop a countervailing narrative in the lighting sector opposed to the Green growth one emerges from the major consideration emerged in the previous section: the expected increases of energy efficiency delivered by new lighting technologies are likely to be inferior to the estimated increase in consumption of lighting

In order to reframe sustainability in the lighting sector we propose to focus on the real meaning of light in daily life (Bowers 1998). Lighting has the purpose to fulfil the human need of performing visual tasks. In this sense, electric light extends the function of natural light in situations in which more light is needed. If one focuses on the ‘function or usefulness of light’ – what we call ‘the functional approach’ to light – we can say that electric light is wasted when: (i) it is used whilst natural light is available (i.e. it is redundant); and (ii) it is not used to perform visual tasks (e.g. illuminate empty spaces).

The functional approach leads to at least two strategies to reduce the demand for artificial light by: (i) increasing the use of natural light when it is available through the rational design of natural light sources in buildings (i.e. reducing redundancy through fenestration) and; ii) adapting/switching off the lights, through Automatic Control Systems (ACS) (i.e. technologies that rationalized the use of lighting) when visual tasks are not performed. These two strategies, by focusing on reducing the demand for artificial light, can be combined with the effort to increase the energy efficiency of lighting bulbs to create three potential strategies (showed in Table 16).

Table 16 Strategies to reduce energy consumption for lighting. The parenthesis indicates the impact on the efficiency and the demand of electric light.

Source of light	
Natural	Artificial

¹⁴ According to McKinsey&Co (2011) the factors that increase light consumption are population increase, urbanization, ageing, rising income, sharing space, and electronic miniaturization. On the other hand, the development of electronic control systems is likely to decrease energy consumption for light.

Use of light	Useful	Better integration of fenestration (- demand)	Increasing efficiency of electric bulb (+ efficiency)
	Useless	Not relevant	Widespread diffusion of ACS (- demand)

The challenge, therefore, is to develop new business models in which all these three strategies are integrated and rewarded for their capacity to produce useful light. The next section focuses on the business model aspects, but before moving there, we briefly explain the meanings and potentialities of the two demand-oriented strategies (i.e. fenestration and ACS).

Fenestration usually refers to the design and construction of openings in a building. Before the 1940s, fenestration was the most important source of indoor illumination (Edwards & Torcellini 2002). Fenestration does not include only windows, but also other old (e.g. skylight, roofless inner courtyard) and modern solutions (e.g. sun-tunnels that combine optic fibres, luminaries and glass structures in order to carry solar lighting beams even in areas in which windows are inadequate or absent). The fenestration concept includes also the Automatic Blind Systems (ABSs) that control the opening of blinds according to the intensity and direction of the direct light. The diffusion of the electric bulb had a dramatic impact on the way in which buildings were designed to use natural and artificial lighting. The birth of the electric light gave new opportunities for building solutions, because lighting could be provided even far from fenestration devices. The electric light became so predominant that today it is used even when natural light is available (Bierman & Conway 2000), especially to control unwanted glare from sunlight. However, literature shows that users seldom restore the original natural daylight conditions when the glare is over (Leslie et al. 2005). The result is that daylight is now often disregarded as a lighting source in modern buildings (Shaw 2010). The development of an alternative frame for building lighting should require the full (re)integration of fenestration, today limited to the field of architecture and building industry, in the lighting industry and the frame of daylight as a 'natural' lighting bulb that as a remarkable efficiency of 93 lm for W (Shaw 2010) for a full spectrum light. Compared to these figures, current fluorescent bulbs have a similar energy efficiency performance but a reduced spectrum of colours.

Another strategy suggested by the functional approach is to minimize the waste of *useless* light from artificial sources through the diffusion and promotion of the ACSs. ACSs are systems that adjust the light quality and quantity according to the inputs received from specific sensors. ACS can achieve a reduction of lighting consumption between 20% and 80% (Galasiu & Newsham 2009, Navigant Consulting Inc. 2012c; Dolin 2013). However the market is still poorly developed (Verify Markets 2011). It is estimated that only 1% of residential buildings and 27% of commercial ones use ACS in the USA (Navigant Consulting Inc. 2012c).

It is worth to notice that the fenestration and ACS are here discussed as separate strategies because of their different impacts (increasing daylight vs. decreasing useless artificial lighting). However the effectiveness of

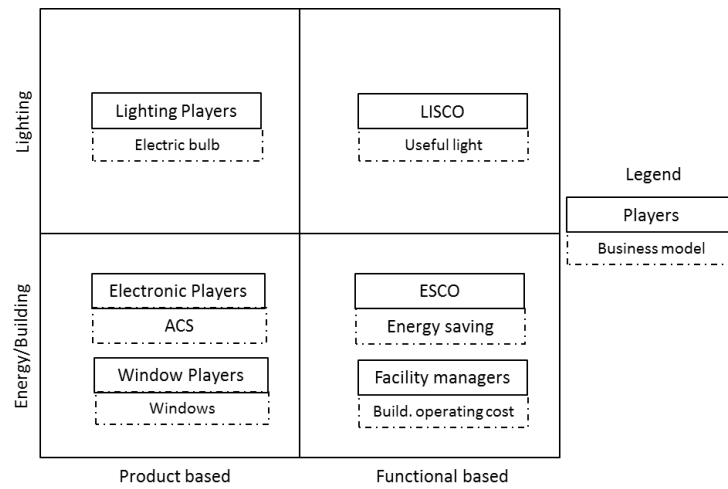
these solutions for energy saving depends on how they are integrated because the quality of daylight (e.g. the degree of homogeneity) that penetrates in a building influences the efficiency of the automatic control systems. Therefore the integration of the two strategies is also a technical challenge that forces to increase the efficacy of the overall lighting system.

Alternative business models

Today the three strategies described above (i.e. more efficient bulbs, fenestration, ACSs) are not integrated. Their integration would require a shift in the current dominant *business models* in the sector in favour of hybrid models that reward both efficiency efforts and demand-oriented measures. Lighting solutions could be evaluated for their capacity to allow users to perform visual tasks and for their capacity to reduce energy consumption. In this sense, providing natural light could be equalized to the provision of artificial light and be rewarded in the same way. Specific meters could be developed to calculate the sum of lumens produced by fenestration devices (i.e., the natural bulb) and the electric bulbs only when the light is actually used for human needs.

This new business model can be developed by new players, the 'Lighting Service Companies' LISCO which aim is to provide useful light by integrating the different sources. The acronym LISCO explicitly recalls the ESCO 'Energy Saving Company' concept, because both approaches have a functional-based business model, but with one relevant difference: ESCO bases the business models on the sale of energy saving, whilst the LISCO focuses on the sale of *useful illumination*. The company Eco-nation is an interesting example of using the LISCO model. By installing the 'Lightcatcher' sun tunnel and a smart meter for free, the company tracks the quantity of saved electricity and gets paid according to the effective savings (EcoNation 2013). The birth of facility/building management market is a second interesting example of a different way of framing lighting. Recently, the International Building Owners and Managers Associations (BOMA) has indicated the reduction of lumens as one strategy to improve the energy performance of buildings (BOMA 2013). Figure 6 proposes a conceptual space to confront the traditional players and the different business models with the LISCO proposal.

Figure 6 . The position of the proposed LISCO player and the new business model in comparison with the traditional players and business models.



The development of the LISCO business model is expected to encounter several barriers, given the dominance of the Green growth narrative. The last part of this section aims at highlighting some of the elements that can influence the development of this alternative model:

Technology

A functional approach requires two types of technologies/solutions: i) technologies that provide light (i.e., LED or other electric bulb, and fenestration); and ii) systems that integrate and manage all these technologies (i.e. ACS).

Regarding the first category, we do not perceive any specific barriers that may hamper the development of these technologies that are today progressing both in terms of efficiency and feasibility.

At systems level instead, the challenge is to develop *smart* lighting system, an acronym used to indicate specific more dynamic lighting controlling systems that focuses on interaction between users, buildings and lighting (Lightolier 2007). For the purpose of our proposal, these systems may provide smart meters and smart sensors able to track: i) the need of light according to the visual tasks performed; ii) the availability of natural light through the different fenestration devices; iii) the need of supplementing artificial light to create the optimal lighting environment; and iv) the provision of lighting from each of the artificial and the natural sources.

The *smart lighting* market is still at an infant stage, and it is expected to exploit the potentiality for customization given by LED. The main trend is to integrate internet and Wi-Fi communications in lighting systems in order to create a dynamic interactive lighting environment. The *smart lighting* perspective gives relevant solutions able to develop the LISCO business model and its focus on the concept of useful light. For instance, a specific *smart* approach can identify the need of lighting according to the actual use of the space: when a person is sitting at a desk, the system may recognize the 'working/reading' condition, and the lighting system may reduce general background light in favour of a directional one. A different approach can be

obtained by tracking personal devices (e.g. smartphone, computers) which communicate personal positions, mood and type of activities. Consequently the lighting system can customize the lighting environment according to the information received by the devices. For example, a user may set a 'reading' mood in its smartphone that allows the lighting environment to adapt at that particular situation/object. The last approach integrates the concept of building zones to predict the usage of specific indoor areas according to the functional use of that space (e.g. a corridor, a bathroom, a living room) at any time of the day.

Those solutions are still far from reaching a technological maturity. We guess that this happened not only because of a specific technical complexity, but partially because the lighting sector has underestimated the importance of controlling systems governing the demand of light, because of the dominant narrative focusing on the supply side.

Policy and society

The policy side has several opportunities to promote a transition towards the functional approach. First, policy makers must become aware of the dynamics of lighting industry. Today lighting demand is usually reported in terms of energy consumption (Bertoldi & Atanasiu 2010). Even if this measurement correctly assesses the environmental impact of lighting, it does not provide information about the dynamics of demand. This is an inexcusable inadequacy, because the governance of any complex markets requires consistent knowledge about the dynamics of both the supply side and the demand one. Therefore policy makers need to be informed about the consumption of lighting (i.e., the quantity of lumens-hours produced) and the related energy consumption. We think that this complete information could increase awareness about the patterns of consumption increase and its effects of the demand of lighting in the last century. Light pollution is a paradigmatic example of the effect of lack of awareness in the political agenda and in measurement systems (Cinzano et al. 2000; Hollan 2009). A remarkable example in that direction is the 'lights out' initiative of Chicago in which tall building night lights are switched off during bird migratory season (Elliott 2013) or the efforts to report data about lumens/h production for the USA lighting market inventory (Navigant Consulting Inc. 2012c).

Second, policy makers shall enforce the integrations of ACSs by setting more stringent building standards about the use of dimming, occupancy and daylight sensors in order to reduce the waste of unneeded lumens. In the USA, the ASHRAE 189.1-2011 norm prescribes the use of automatic systems to reduce light intensity at least by 50% when no one is present (Jouaneh 2013).

Third, policy makers should also promote the functional approach by setting a mandatory lighting label for building which indicates the performance of the building in providing natural illuminations, and managing the artificial ones. Such information could actually lead to policies that set more stringent standards for quantity of natural lighting in building (and quality for the artificial one).

Lastly, a paradigmatic shift should occur to change the idea that the electric bulb is the only source of light. Policy makers should promote new lighting organizations that include all the lighting actors, not only the ones associated to the electric bulb. Such actors may ease the transition by bringing different narratives and technologies in the lighting arena. For instance, the 'Liter Bottle Lamp' designed by the MyShelter Foundation

is a case of reframing of fenestration as a lighting solution that relies on frugal engineering that reduces material use and meets social needs (Sharma & Iyer 2012). By adapting a used plastic litre bottle, it is possible to have a lamp equivalent to a 60W incandescent bulb, but with no need for electricity (MyShelter Foundation 2013). From September 2011, around 15,000 'Liter Bottles' were already providing sun-light to thousands of simple dwellings in the slums of Manila. We do argue that MyShelter Foundation is a lighting player and the Liter Bottle is a lighting technology.

Taxation

Energy tax should target reduction of energy consumption (for lighting). Tsao et al. (2010) propose to stabilize energy price through the raise of taxation every time that efficiency increases. Since lighting demand depends on the energy price and not on the energy efficiency, this approach would sterilize the increasing demand for lighting due to increasing of efficiency. We share the importance of this proposal but we highlight that this is a partial answer, because there is also the need to reduce the consumption of (useless) light, even if efficiency is stable.

We indicate two ways in which the proposal of Tsao et al. can be updated to include the incentives to reduce the demand of (useless) light, not depending on gain of efficiency. First, energy taxation may increase every time that energy consumption does not follow an established pattern of reduction. Therefore the locus of taxation is not the gain of efficiency, but the missing reduction of consumption. Taxation, however, has a relevant redistributive effect that can create conditions of unfairness, given the different incomes and consumption baskets of consumers. A fairer, but more complex solution, would be to separate the taxation on consumption of useful light from the taxation on the consumption of useless light, in which the former shall follow the proposal of Tsao et al., and the latter shall be taxed as a luxury good. This system may be considered much fairer than the former one, but it has an evident shortcoming: the evaluation of useful and useless lights requires a complex assessment system with high associated transaction costs.

A last remark regards the critical difference between the implementation of the three strategies in new constructions or through building renovation. The latter may have relevant costs if it regards new fenestration devices. In this case, higher taxation on lighting may turn not to promote such transformations, because of the insurmountable costs of building renovation. As a result, we highlight the importance of the labelling systems and the proposed taxation mechanism for the new constructions, whereas further considerations are required for the case of existing building stock.

6. Concluding remarks and future research

In this work we show that the notion of environmental sustainability is far to be an objective and monolithic concept but is the contested ground of competing interpretations framed in turn in a number of what we have called *sustainability narratives*. The deconstruction of those narratives, we argue, is crucial to understand the dynamics that shape certain sustainability discourses and, above all, the interests and the actions of the actors involved in the process. The important function of discourse in this formulation is its constitutive nature: language does not simply represent the world but enables world's transformation through action. In the

present work we show that is possible to open up the debate about a sustainable future reframing the relations between technical change and demand/consumption in multiple ways.

Another important contribution of the present work is the application of the analysis of multiple narratives of sustainability to the lighting industry that is potentially useful to the formulation of alternative business models for the sector. By analysing the current trends of the lighting sector, we conclude that the dominant Green growth narrative is not enough to achieve an absolute decoupling. We propose a number of alternatives to reconcile the efficiency perspective with measures that are designed to decrease the demand. In this sense, we indicate a conceptual change of the lighting sector from being the realm of the electric bulb to a more integrated perspective in which natural and artificial sources of lighting are fully integrated. In this way, conservation and efficiency measures refer to electric lighting, whereas increasing of demand refers to the use of natural light. LED plays a pivotal role in leading such transition, because it is a semiconductor electronic device which can be fully controlled by centralized/decentralized systems. LED has therefore the potentiality of being the future green technology, not for its improved energy efficiency, but for its capability of promoting systemic lighting solutions. The possibility of this technology to fulfil such expectations will depend on the evolution of the dominant lighting narrative towards a more integrated one. This shift would imply major transformations of current policies, practices and actors, with the development of new capabilities and new markets coming from the integration of the traditional lighting and fenestration sectors.

We acknowledge that our results are limited both in methodology and in the theoretical dimension. From a methodological perspective, we already highlighted that we did not include other environmental dimensions besides the dimension of energy efficiency. An analysis of the whole lifecycle of the lighting technologies might achieve more accurate results. Similarly, we did not address the specific differences between the residential and the non-residential lighting markets. Our analysis focuses on the latter because the residential market posits two relevant challenges for our conclusions. First, the incandescent technology is still dominant in the residential market. Consequently the expected gain of efficiency resulting from widespread diffusion of LED is much higher than what we indicate in this paper. This different pattern may lead to different conclusions about the degree of sustainability of an eco-efficiency based narrative. Second, the consumption of energy of each dwelling/house is by far lower than the one in non-residential settings. This different magnitude implies that the functional business model may be unrealistic to be applied when the expected savings are too low. This is exactly what happens today about the ESCO business model, which is not getting popularity in residential settings. However, we highlight that the residential market is yet the most important market in terms of installed bulbs, but it represents only 8% of demand for lighting and 25% of demand of energy for lighting (Navigant Consulting Inc., 2012c). Such figures suggest that the non-residential markets (i.e. outdoor and non-residential indoor) are by far the most important when we deal with sustainability.

From a theoretical perspective, we did not fully exploit the potentiality of the Discourse analysis, by explicitly analysing the notions of *power* and *democracy* in the discourse of lighting. Foucault, who forged the term *governmentality* to describe the capacity of language as social practice to govern and control the actions of third actors (Foucault 1977; 1984), indicated that the discourse can be used to legitimate, reinforce or exclude specific social practices. The introduction of the notion of governmentality in the analysis of environmental

politics discloses the role of formal institutions i.e., governmental agencies and universities in the legitimization of science-based policy making. By reframing the environment as a highly complex system that can be understood only by experts, the sustainability debate ends up excluding vast sectors of civic society. The acknowledge that sustainability is a contested notion, as Hajer & Versteeg (2005) suggest, is the base to make a call for opening up the debate to the inclusion of alternative narratives constructed around a wider range of actors from the civil society i.e., NGOs, local communities and social minorities (Stirling 2007). A more accurate analysis of the public discourse of the dominant player in the sector of lighting might shed light on the dynamics beyond the acceptance of the Green growth narrative within the industry but also among institutional actors like governments and consumers. Furthermore, another important limitation is that our analysis is designed to focus on developed countries. This is certainly a narrow goal since in the next future developing countries, hungry for new lighting applications, will become increasingly influential in the production, distribution and consumption of energy for lighting. How this will affect the present dynamics of the lighting industry is still an uncharted territory.

Article 4. The green journey of indoor light and lighting. Future Visions among professional experts.

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Abstract

Policy makers expect to reduce the consumption of energy in the provision of light. Consequently, many innovations are today presented as promising, because of their interesting energy performances. Nevertheless, recent literature indicates that many promising eco-efficient innovations did not reduce the consumption of energy for lighting.

We investigate the present expectations about the future of the Danish non-residential lighting market, through a cognitive approach based on interviewees with experts. Results confirm the importance of a political commitment towards energy saving, and the potentiality of some promising innovations, as the LED technology and the development of a the *smart* light system, to deliver important energy saving within the next two decades. However, our methodology pointed out that the birth of the future *smart* LED system will increase the importance of other trends (e.g. effects of light on human productivity, comfort, and visual experiences) in connection to the provision of light. These trends are expected to increase the demand of light, especially when a new class of lighting players will develop and will fully exploit the potential applications of these innovations. We conclude that the final impacts on energy consumption may be uncertain. Therefore, we highlight that energy saving policies, which focus only on supporting the development and diffusion of promising innovations, may be myopic, because they do not consider the possible creation of new uses and practices in the use of light.

1. Introduction

The provision of light is one of the societal needs that is expected to reduce the consumption of energy (EPA, 2011; European Commission, 2012; IDA, 2011; Oosterhuis, 2007), with expected potentiality of saving up to 70% respect to the current level (European Commission, 2011). Consequently many lighting innovations have attracted the societal attention due to their promising benefits for energy saving (Bertoldi and Atanasiu, 2010; EPA, 2011; Haitz and Tsao, 2011; Menanteau and Lefebvre, 2000; Wall and Crosbie, 2009; Weiss et al., 2008).

However, several scholars highlighted that past increases of efficiency did not actually reduce the consumption of energy for lighting (Nordhaus, 1998). Tsao and Waide (2010) reviewed three centuries of energy consumption for light and concluded that there is a massive rebound effect associated to an increased efficiency in the provision of lighting. Fouquet and Pearson (2006) identified four distinct revolutions in lighting services, and in each of them the demand of light skyrocketed. Furthermore Tsao et al. (2010) indicated that there are not sign of saturation in the future demand for light, warning about massive future rebound effects.

Given the hope to reduce energy consumption through the diffusion of promising lighting innovations, and the contrasting findings of the rebound effect literature on lighting services, it is not trivial to question to which extent such promising lighting innovations will be able to fulfill their promises. The eco-innovation literature does not help solving the puzzle, because this literature has shown different positions and conceptual weakness in evaluating innovations which generate complex environmental impacts. Pearson and Kemp (2007) proposed a very popular definition of eco-innovation as any innovation *“which results, throughout its life cycle, in a reduction of environmental risk, pollution and other negative impacts...compared to relevant alternatives”*. According to the same authors, such definition implied that *“the majority of technological innovations probably offer environmental benefits”* (p. 5), because *“all new processes that are more resource efficient are eco-innovations”* (p. 7). Indeed, according to that definition, all the past and expected technological revolutions in the provision of light shall be labeled as eco, because of their capability to increase energy efficiency, even if the actual result was to increase energy consumption. Hekkert et al. (2007) proposed a less optimistic interpretation, because they indicated that *“current uses of technologies often have severe negative effects”* (p. 414) and they argued for the guidance of the innovative process towards sustainability. Two visions about eco-innovation occur. According to Pearson and Kemp, efficiency is the main criterion of evaluation of the ‘eco’ dimension, so the normal course of the innovative process is to produce eco-innovation. According to Hekkert et al., the innovative process often produces severe negative environmental effects, so it needs guidance. In an attempt to combine the two positions, Carrillo-Hermosilla et al. (2010) conceptualized three different forms of eco-innovation: i) an end-of-pipe form based on component addition to address specific problems; ii) an *eco-efficient* form that focuses on optimization of productive processes (Ang et al., 2010; Patterson, 1996; Wuppertal Institut, 2009); iii) a *systemic* form (eco-effectiveness) in which innovation addresses changes that guarantee the effectiveness reduction of environmental burden at the level of society (Fölster and Nyström, 2010; Geels, 2011). Carrillo et al. indicate that the goals of the eco-efficiency innovation *“however admirable, are often regarded as insufficient in so far as increases in environmental efficiency tend to be erased by subsequent growth (rebound effect)”* (p. 1076), while the systemic form is more sustainable over the long term

because it “*challenges companies and society at large to redefine their production and behavioural patterns*” (p. 1076).

Carrillo et al. defines the systemic form of eco-innovation in two different dimensions. The first includes the impact of innovation on consumption (the well-known rebound effect). The second indicates the need of radical changes to limit the rebound effects. This paper lies on the intersection of the positions of Tsao et al. and of Carrillo-Hermosilla et al. We share with Tsao et al. the idea that future lighting revolutions may promote new and more intensive uses of light, so it is essential to investigate expected patterns of energy consumption for future lighting scenarios. We share with Carrillo-Hermosilla et al. the idea that an effective eco-innovation can be understood only through the analysis of the relations between innovation and consumption.

Through the paper, we explain the different contributions of the two perspectives on eco-innovation, the eco-efficiency (or the Pearson and Kemp) one, and the systemic one of Carrillo-Hermosilla et al., to understand the different impacts of future innovations on energy consumption in the provision of light. For that reason, we interviewed professional experts which produced individual cognitive maps representing future practices for lighting in the Danish context. The maps were used to assess: i) the contribution to energy saving of the different dynamics for the future lighting sector (i.e. the eco-efficiency perspective); ii) the relationships between the dynamics (i.e. the eco-effectiveness perspective).

The eco-efficiency form indicates that technology and policy are important dynamics for energy saving, while more attention to quality of light, human health and effects of light on productivity is expected to increase the demand of light. The relationship analysis indicates that these dimensions are intertwined. By way of example, LED technology is expected to open new light opportunities that will demand more energy, especially when new players will arise to fully exploit the opportunities of this technology. The overall picture confirms the complexity of the future lighting scenario, which lies on the interconnections between technologies, policies and practices. The existence of such relations indicates the possibility of contradictory and unexpected dynamics for energy saving, especially if in a mid/long-term horizon. An important finding of the relationship analysis is that LED technology is not only considered more efficient than other lighting technologies, but it is also considered superior in respect to many dimensions (e.g. versatility, customizability), so it is expected to encourage new practices that will increase the demand of light.

We conclude that the systemic form of eco-innovation, as defined by Carrillo et al., is the most valuable approach to predict environmental dynamics when practices and technologies are closely intertwined. Similarly, the concept of eco-innovation defined by Pearson and Kemp seems too simplistic in our context and it may mislead policy makers in their attempt to design policy to improve environmental sustainability. Two suggestions follow. For future eco-innovation studies, we indicate that the integration of the rebound effect literature can be very beneficial in highlighting complex environmental dynamics. For policy makers, we suggest to carefully judge the impacts of innovative policies in respect to new practices in the society, in order to predict potential unexpected outcomes of policies that are designed to reduce environmental burden through fostering efficiency.

Section two briefly contextualizes the discourse about energy, light and lighting in Denmark. Section three introduces the methodology. Section four presents the results of the case study, and section five discusses them. Section six concludes and highlights the main findings and limitations.

2. Background: Light and lighting discourse in the Danish context

The empirical study was carried out with professionals that work in Denmark. Denmark is a small, industrialized EU country with relatively many small and medium sized companies, trade and service industry, high wages, high taxes, a relatively equal income distribution, a well-developed labor market and an emphasis on social cohesion and welfare (Christensen et al., 2008). This includes a developed tradition for regulation of building and of working environment. These aspects are reflected in the discourse of light and lighting in non-residential buildings on an overall level. In addition to this, especially two aspects of the light and lighting discourse in Denmark in recent years must be mentioned before turning to the specific results of our analysis: Electric light as important area for energy savings; and natural light as integrated element in architecture and building design. These have been prominent and influential sub-discourses in the recent years, to some extent independently of each other, to some extent connected.

While there is probably no doubt that the use of artificial light and the number of installations has actually increased over the latest four to five decades, it is in the general societal discourse the electricity saving dimension that has been most visible and explicit. It has figured relatively high on the agenda in policy, media and general public discussion. Since the oil crisis in the 1970s, policy efforts for energy efficiency and energy savings have been established in Denmark. Considerable energy efficiency gains have appeared. In some periods, to the extent that the total energy consumption decreased despite economic growth (ENS 2008) and Denmark is now among the most energy efficient countries in EU and OECD (IEA, 2011, 2006). The goal for the period from 2010 to 2020 is a reduction in total energy consumption on 7% (transport excluded) (KEB, 2012a).

Though lighting does usually not appear explicitly as an individual policy area (KEB, 2013, 2012b; Regeringen, 2001), it is considered one of the important sub-areas for energy savings in governmental action plans for energy savings (TEM, 2005). Lighting constitutes in the order of 5% of the total energy consumption and an estimated saving potential of 24% over a 10 year period from 2006-2015 and thereby 5-6% of the total savings on national scale. The connected potentials for private economic savings are estimated to be 60% of the current costs in the long term. Analyses have shown that within business and industry, lighting constitute 21% of total electricity consumption; highest within trade and service industries with 43% (Rizzo and Johansson, 2008, p. 16). Also for public institutions, offices, etc. lighting accounts for a large share, between 25% and 50%, of the electricity used (Munck and Clausen, 2008, p. 5).

Denmark was one of the early movers concerning public support programs for compact fluorescent lamps (CFLs) in the 1980s and 1990 as alternative to incandescent bulbs. In the mid-1990s, Denmark had the second highest CFL ownership rate in the world (Martinot and Borg, 1998). Light sources were one of the first focus areas for EUs and Denmark's energy labelling schemes for products. In the public support program for research and development projects about energy saving and efficient energy use, lighting is one of the seven prioritized areas. The area received 16% of the total funding in the period 2002-2011 (Dansk Energi, 2012).

The use of natural light in architecture and building design is not to the same degree as electricity savings a specific effort area within governmental policy. It is broader institutionalized and embedded in architectural practices and in regulations and norms in the building area. Through amongst other things the architectural styles of functionalism and modernism, a tradition of natural light as central element in building design and relatively large windows developed in the 20th century. There is today used more glass in new buildings in Denmark than ever before and like in many other countries, there is a tendency to large glass facades, not least in new office buildings (Johnsen, 2002; Johnsen et al., 2011).

Since the first national building code was established in 1961 there have been regulatory requirements of a certain amount of window surface and natural light in workrooms as well as habitation rooms (Boligministeriet, 1961). In the recent years, the interplay between natural light and electric lighting has been further specified in the building code through functional requirements, with natural light as the primary and preferred type of light and electric light as supplementary (EBST, 2008, 2006). While the connection between natural light and energy was earlier primarily a heating matter (loss through windows), the connection with electric light and reduction of electricity consumption is now clearly described in the building code. It is a requirement that the light and lighting shall be energy efficient (DECA, 2010). In addition to being a matter of satisfactory light for the use of the rooms and an energy matter, windows and natural light are also in the building code described as an issue of health and well-being, among many others.

3. Methodology

This section explains the methodology, and the delimitation of the case study. It also indicates how data have been collected, analyzed and validated.

The methodology was designed to collect information about future lighting technologies and practices. Technologies and practices were assessed as single elements and in respect to their mutual connections. Since several major innovations are expected to occur in the coming years, the investigation of future patterns was not performed through the extrapolation of past patterns, but through the collection of expectations among professional experts. Indeed, Miles and Huberman (1994) argue that the richness of the information derived from the interviews has the strength to reveal critical interactions of complex social phenomena.

We argue that the goal of framing and developing eco-innovation within the lighting sector is the result of the interaction among different categories/functions. Each function/category has its own unique contribution to make to strengthen the innovation processes of the lighting community. The interactions between the many functions are intricate and critical in sparking action on understanding the greening of the sector. However, these functions and categories do not exist in a vacuum, they exist as knowledge in the mind of the different actors that interact (Jorna, 2006). Therefore, the individual remains as the main source of knowledge (Rosales, 2012).

We used a cognitive map technique (Tolman, 1948), which allows exploring the individual perspectives about future lighting scenarios. Cognitive mapping can be defined as a process composed of a series of psychological transformations by which an individual acquires, codes, stores, recalls, and decodes information about the relative locations and attributes of phenomena in their everyday spatial environment (Downs and Stea, 1973).

The cognitive approach has been already applied in connection to innovation and technological foresight (Boe-Lillegraven and Monterde, 2014; Bootz, 2010; Kaplan and Tripsas, 2008; Swan, 1997). It is best to construct cognitive maps with reference to some particular question, which it is called the focus question. In the present study, we presented to several lighting actors with a question that is relevant in their professional domain: *“Imagine that you have to explain your perspective about the use of energy for indoor non-residential lighting in 2030 to a client who knows little about the subject. Which elements would you take in account?”*

The year 2030 was fictional, and it represented a date that was considered not too close or too far in the future. The interviewers were aware of the fictional role played by it. Nevertheless, the indication of a year was needed to avoid different subjective interpretations from the interviewers in respect to the concepts of short and mid-long term terms.

The choice to narrow the analysis to indoor non-residential lighting was the results of different *ex-ante* considerations about trends in the lighting market. First, the residential and non-residential value chains are very different, with different players, business models and users' behaviors. Second, the lighting markets show very different degree of efficiency in the use of lighting technologies (Navigant Consulting Inc., 2012a). Incandescent/halogen is still dominating the residential market, whereas the fluorescent one dominates the non-residential one. The different technological regimes make the two segments hardly to compare. Such issue was confirmed by all the interviewees, which highlighted that their thoughts should not have been applied to the residential market as well. The focus of the case study on a country (Denmark) was due to the fact that the national level still matters in the usage of lighting, because of the regulatory framework (e.g. the role of building code) and of the different climate conditions, among other factors.

A total of 17 experts were face-to-face interviewed. Interviewees were selected, among professional experts, to represent different knowledge areas and roles. They were 7 women and 10 men, between 27 to 62 years old. Interviewees work in Denmark and they had different background: electricity, engineering, design, building, architecture, marketing and research. They performed different roles in companies and research institutions. Each interview lasted between one and two hours, and it was audio-recorded for further listening. Participation was voluntary. The only incentive to encourage participation was the promise to give to each of them the personal cognitive map. The interviews included fourth phases, each of them with a specific deliver. The interview guide can be found in Appendix A.

First phase

The interview started with a brainstorming session in which the interviewee was asked to write down on sticky notes the main important elements of future lighting practices in non-residential indoor buildings in 2030. The interviewer did not mention the aim of addressing energy savings, therefore participants were encouraged to present any important elements, even in form of wishes. Participants were asked to include only one element for each sticky note. By way of example, they were suggested not to write complex sentences like “Technology A to improve comfort in offices” in a sticky note, but to use different sticky notes for each element (in the example three sticky notes for each element: technology, comfort, office).

Second phase

The interviewees used a blank A2 paper sheet to freely position the sticky notes on, and to draw arrows (representing relations) between them. The direction of the arrow represented the direction of the influence. For example, an arrow going from A to B meant “The development of A will influence the development of B”. The interviewees could design as many arrows as wished, without any limitation. In that phase, interviewees were still allowed to add elements that were not mentioned during the first phase.

Third phase

The interviewees assessed each element note through two dimensions: i) the potential for energy savings; ii) the feasibility of development. For each of the two dimensions, interviewees could use a low/medium/high scale.

Fourth phase

The interviewer reported the sticky notes on a Cartesian coordinate system in which the two dimensions were represented through the scale (low, medium, high). The interviewer also reported the arrows as designed by the interviewee. The interviewee was asked to give some thoughts and general explanations on the overall map.

All the phases were kept separated. Any materials used during a phase were not showed during the previous phases. The reason to do that was to avoid contamination between the aim of the interviewer and the interviewees. Therefore, the overall picture (i.e. the cognitive map) was only presented during the fourth phase by the interviewer.

In order to guarantee the validity of the answers we obtained, we followed the directives proposed by Wolcott (1990) during the knowledge elicitation process: i) elaborate an interview guide, ii) pre-test the interview guide, iii) avoid the modification of the interview guide structure during the interviews, iv) listen carefully, v) produce annotations that are as precise as possible, vi) write on an early way, vii) employ a unique format to transcript the interview, and viii) corroborate the information with the interviewee.

The validation of the final results was confirmed by *ex-post* evaluation of the interviewees. After one week, the interviewer sent a two pages report including the individual cognitive map and the main interpretations given by the interviewer. Interviewees were asked to evaluate the degree of agreement using the following 4-point Likert scale: 1. Total disagreement; 2. Disagreement superior than agreement; 3. Agreement superior than disagreement; 4. Total agreement. We asked the interviewees to give frank answers and not to please the interviewer, highlighting the importance of honest evaluation for the scientific analysis. Two interviewees gave “two”. The rest gave “three” or “four”. Among the two negative respondents, one highlighted that the final map was too complex to be useful; the other said that the map was too obvious to be useful.

Once the interviews were validated by the interviewees, we started the analysis. It was performed through a combination of quantitative and qualitative steps. The first step was to group elements in 14 categories in

order to standardize similar elements and allow comparisons between interviewees. The interviewers categorized elements through a qualitative process. In fact, elements were classified according to the degree of homogeneity that depended on; i) the actual written content of each sticky note and; ii) the interpretation given by the interviewee when the content was unclear or overlapping. This last step has been performed through the listening of audio transcripts.

Resulting data were analyzed through Excel 2010 and Gephi 0.8.2, an open-source software for socio-network analysis. The analysis of the relations was also subject to a qualitative interpretation from the interviewers. In fact, the map only indicated the direction of the influence, but it did not indicate if the influence was positive (reinforcing) or negative (weakening). The interviewers interpreted the type of influence by the dialogue with the interviewees.

Excel was used for the descriptive analysis, in which each element was associated to one category, and the categories further analyzed to identify:

- The popularity of a category, given by the analysis of the number of elements for each, and the numbers of interviewees mentioning it
- The potential for energy saving of a category, calculated according to the potential for energy savings of each element in that category
- The feasibility of development of a category, calculated according to the Feasibility of each element in that category

Gephi 0.8.2 has been used to perform the network analysis, which is the analysis of the relations between the elements (and the categories). The network analysis of the categories is actually a representation of the network analysis of the elements. In fact interviewees drew relations between elements, and not between categories. The network analysis has been used to produce the following popular network metrics:

- Degree value, which is the number of edges (i.e. relations) for each node (i.e. category). Since the interviewees produced directed graph, it was also possible to evaluate the in-degree value (i.e. the number of incoming edges) and the out-degree value (i.e. the number of outgoing edges). Nodes with a high degree value indicate that they have more connections in the system. Among them, nodes with a high in-degree value (the listeners) are highly directly influenced by the system; nodes with a high out-degree value (the talkers) have important direct influence on the other nodes. The degree value can be further elaborated as 'weighted degree value' that represents the degree value adjusted for the sum of the weights of the edges.
- Betweenness centrality, which is a measure of the degree to which a node lies on the shortest path between two other nodes. High betweenness indicates that the element has an high influence in the network.

Betweenness and (weighted) degree are widely used centrality measures (Freeman, 1977). The degree measure indicates how many nodes are in contact with a specific node. Betweenness indicates the capability of a node to control the resource of the network. In fact, high betweenness means that a node is able to influence many connections between other nodes.

4. Results

Results section is divided in two main sub-sections. The first reports the descriptive analysis of the categories. It includes an analysis of the main elements, and of the specific evaluation in respect to potential for energy saving. The second part analyses the relationships between the different categories. Both the sections have a specific focus on the energy saving dimension.

The descriptive analysis

A total of 17 experts have been interviewed. They produced 17 individual cognitive maps containing 217 elements (i.e. sticky notes) and 381 relations. The 217 elements have been grouped in 15 categories¹⁵ (see Table 17). The following table represents the final list of categories and a short description of each.

Table 17 List of categories and description

Category	Main elements included
Economy	Price, cost, markets, business models and general market considerations
Dynamic light	The construction of the automatic light system (e.g. controlling sensors, intelligent light, system management, software, light zoning) representing the future <i>smart</i> components of lighting
Technology of electric bulbs	Components, technologies and other elements of new electric bulbs
Quality & Comfort	Considerations about comfort of users and quality of light
Policy	Policy and wider societal issues (e.g. specific motivation, sustainability) (excl. building regulations)
Light players	Actors and their specific actions (e.g. lobbying, cooperation) in the lighting market
Customized light	Light as a customized product (from the system) to the users' needs and

¹⁵ Actually we defined *ex-ante* a list of 8 categories (Daylight, Design, Light Management, Market Dynamics, Policy and society, Tech Efficiency, User, Other), but we found that new categories were needed; therefore we created the new list of 15 categories.

	moods
Daylight	Components and technologies for harvesting and using daylight
Integrated light sources	Development of new light sources which goes beyond the traditional concept of lamp (e.g. walls that emits light)
Building regulation	Policies and regulation about buildings
Aesthetic/Emotion	Elements related to the beauty of light
Health	Considerations about human health
Human productivity	Light as element of human productivity
Individual controlled light	Considerations about the capability of users to regulate and adjust light
Other	Non-classified elements

Table 18 reports the main information for each category: number of elements included, number of interviewees who used each category, potential for energy saving, and feasibility of development.

Table 18 Characterization of categories

Category	Nr. elements	Interviewees mentioning it	Pot. for energy saving			Feasibility		
			Low	Med	High	Low	Med	High
Economy	33	14	12,1%	33,3%	54,6%	18,2%	27,3%	54,5%
Dynamic light	28	16	7,1%	39,3%	53,6%	0,0%	42,9%	57,1%

Technology of electric bulbs	23	17	0,0%	30,4%	69,6%	4,3%	21,7%	73,9%
Quality & Comfort	22	13	54,6%	36,3%	9,1%	4,5%	36,4%	59,1%
Policy	19	12	0,0%	10,5%	89,5%	10,5%	26,3%	63,2%
Light players	17	9	17,6%	41,2%	41,2%	0,0%	41,2%	58,8%
Customized light	16	10	37,5%	37,5%	25,0%	12,5%	50,0%	37,5%
Daylight	13	10	0,0%	46,2%	53,8%	23,1%	46,2%	30,8%
Integrated sources	10	8	30,0%	60,0%	10,0%	20,0%	40,0%	40,0%
Building regulation	10	8	10,0%	20,0%	70,0%	0,0%	30,0%	70,0%
Aesthetic/Emotion	8	6	62,5%	37,5%	0,0%	12,5%	75,0%	12,5%
Health	7	7	71,4%	28,6%	0,0%	0,0%	71,4%	28,6%
Human productivity	5	5	60,0%	20,0%	20,0%	20,0%	40,0%	40,0%
Individual controlled light	5	5	20,0%	20,0%	60,0%	20,0%	20,0%	60,0%
Other	1	1	100%	0,0%	0,0%	100%	0,0%	0,0%

Table 19 summarizes the elements according to the evaluation of feasibility and potential of energy saving. Only 3 elements (1.3% of the total) rank 'low' for both the dimensions. This means that the proposed dimensions were important criteria to understand interviewees' answers. In fact, only these 3 elements seem not relevant according to the two dimensions.

Table 19 Number of elements for each possible combination of energy saving and feasibility

Count of elements		Feasibility			
		Low	Medium	High	Total
Pot. for energy saving	Low	3	23	20	46

	Medium	10	36	27	73
	High	8	22	68	98
	Total	21	81	115	217

The rest of the section illustrates the content of each category and the evaluation according to the two proposed dimensions (see Table 19). The content is gathered by the sticky notes and the audio records. The assessment of potential for energy saving and feasibility derives from the value given by the interviewees.

Economy

This category includes 33 elements, and it is used by 14 interviewees. It shows a significant potential for energy saving and good feasibility. Interviewees indicate that cost saving is the most important reason for energy saving, and that increasing efficiency is strategy to reduce energy consumption and cost. The economy dimension has a drawback in terms of consumption. Users may still purchase less efficient lighting technologies because of the lower purchasing price. Interviewees highlight that the positive impacts on energy saving can occur if users adopt a long-term cost perspective. Therefore some interviewees indicate that more informed consumers and diffusion of new business models (e.g. long term perspective, and move to a functional-based lighting service) encourage energy saving.

Table 20 Elements in the economy category

Elements for economy		Feasibility			
		Low	Medium	High	Total
Potential for energy saving	Low	1	1	2	4
	Medium	2	5	4	11
	High	3	3	12	18
	Total	6	9	18	33

Table 20 shows that elements with high potential for energy saving are often the ones expected to be fully developed (high feasibility). Therefore interviewees indicate that the positive dynamics of energy saving (focus on efficiency, cost savings, and long term perspective) are very likely to be developed, whilst the potential drawbacks (negative impacts of purchasing price for better lighting technologies) seem less relevant. Finally, Table 20 shows three 'missing opportunities', defined as elements with high potential but low feasibility. The lack of focus on quality of fixtures is the first missing opportunity, because it can improve energy performance over the life cycle of a fixture. The second missing opportunity is the excessive focus on installed watts instead of the used ones. This happens because, during the purchasing phase, users usually do not buy an excessive number of watts (e.g. they avoid lamps with too high wattage), but they tend to forget that energy consumption depends also on the daily practices. One interview also mentioned that energy efficiency is a missing opportunity, because of the short-term perspective of consumers purchasing behaviors.

Dynamic light

This category includes 28 elements, and it is used by 16 interviewees. It shows a good potential for energy saving and high feasibility. The dynamic lighting will play an important role for energy savings because it includes the idea of 'smart light' that is the ability of future lighting systems to control the light in a way in which only the useful one is actually produced. Some concepts appear central in this category. Interviewees expect that future light will use more sensors to control the environmental conditions. The controlled lighting environment will also depend on the diffusion of light management planning activities and specific software. The combination of new software, technologies and management practices will change the light from being a sum of individual controlled bulbs, to a complex and integrated system. The only major drawback, in respect to energy saving, is that the smart light concepts will create more lighting opportunities that may increase the demand for lighting.

The combination of the feasibility and potential dimensions confirms that the smart light system is going to happen (no elements with low feasibility) and that energy saving is an important future (only two elements with low energy saving).

Table 21 Elements in the dynamic light category

Elements for dynamic light		Feasibility			
		Low	Medium	High	Total
Potential for energy saving	Low	0	1	1	2
	Medium	0	4	7	11
	High	0	7	8	15
	Total	0	12	16	28

Technology of electric bulb

This category includes 23 elements, and it is cited by 17 interviewees. It is the only category that has been cited by all the interviewees. It indicates a very high potential for energy saving and a very high Feasibility. There is a common view that all the new technologies will lead somehow to save energy, as indicated by the lack of elements in the low value for energy saving. The diffusion of LED technology is central in the expectations of all interviewees. Some of them do differentiate between LED and OLED (organic LED), whilst others indicate OLED as the evolution of LED. Among the first, there is the idea that OLED is a different technology that will allow the integration of lighting sources in different surfaces and contexts. Therefore OLED is expected to drastically change the concept of light, even in respect to LED. Future lighting applications will mix OLED, used as general background and 'bulbless' light, and LED, used in more traditional bulbs. Among the second, there is the idea that OLED will just replace LED, but this process is slowly and beyond 2030, because LED is ready, whilst OLED is still in an infant stage. The combination of the feasibility and potential dimension gives a very positive energy outlook, with no elements ranking low for energy saving.

Table 22 Elements in the technology of bulb category

Elements for technology of electric bulb		Feasibility			
		Low	Medium	High	Total
Potential for energy saving	Low	0	0	0	0
	Medium	1	4	2	7
	High	0	1	15	16
	Total	1	5	17	23

Quality & Comfort

This category includes 22 elements, and it is cited by 13 interviewees. It shows a low potential for energy saving and pretty significant feasibility. Quality and comfort are essential components in the design of future lighting scenarios. These dimensions are expected, with few exceptions, to increase energy consumption. Among the elements increasing energy consumption, interviewees expect a trade-off between efficiency and quality of light. Indeed, the increase of attention towards quality of light will reduce the attention towards the adoption of the most efficient lighting technologies. Among the positive impacts for energy savings, interviewees indicate that consideration about thermal comfort will be more part of the design of lighting system. In the future this consideration will encourage the diffusion of more efficient lighting technologies which do not impact on the thermic conditions of environments.

The increasing attention towards light quality is expected to encourage the replacement of fluorescent tubes with the new LED technology. Interviewees indicate that the fluorescent technology is pretty bad in respect to quality of light. As result, attention towards quality will encourage the adoption of the more efficient LED technology. These complex dynamics are reflected in the different elements of this category (Table 6).

Table 23 Elements in the quality and comfort category

Elements for quality&comfort		Feasibility			
		Low	Medium	High	Total
Potential for energy saving	Low	0	5	7	12
	Medium	1	2	5	8
	High	0	1	1	2
	Total	1	8	13	22

The trade-off between quality and efficiency is widely expected among experts, as indicated by the presence of 12 elements with low potential for energy saving. Instead only two elements indicate the positive impacts of comfort and quality for energy saving. Overall speaking, quality and comfort are expected to not contribute at the reduction of energy consumption for light.

Policy

This category includes 19 elements, and it is cited by 12 interviewees. It shows the highest potential for energy saving and pretty significant feasibility (Table 7). All interviews share the idea that policy plays a role in promoting energy saving. The majority indicates the importance of the sustainability discourse in policy and society, as driver of energy saving. The most expected policies will focus on (energy) taxes, new light standards and green public procurement. There are only two political issues that do not contribute to save energy. The first is the risk of a greenwashing perspective that may lead policy makers to promote ineffective solutions. The second is that light pollution can still increase, because policy makers show lack of awareness about the lighting pollution phenomenon.

Table 24 Elements in the policy category

Elements for policy		Feasibility			
Potential for energy saving		Low	Medium	High	Total
	Low	0	0	0	0
	Medium	1	1	0	2
	High	1	4	12	17
	Total	2	5	12	19

The elements with a high positive impacts on energy saving have a high feasibility, indicating an optimistic view for the future. Table 24 shows one ‘missing opportunity’, that is the lack of focus of funding ‘bigger’ research projects. In the view of one interviewee, policy focuses too much on funding small projects with a questionable impact on the capacity to deliver positive benefits, whereas investing on fewer bigger projects will provide the needed critical-mass to achieve important impacts.

Light players

This category includes 17 elements, and it is cited by 9 interviewees. It indicates an average potential for energy saving and good feasibility. Interviewees think that the lighting value chain is going to change. Lighting designer will become important players, because they have the needed knowledge to design and plan future light systems. Lighting designers will cooperate more with architects and lamps manufactures. For some, lighting designers will emerge as a new category of player, whilst the rest expects big lighting players to acquire such competences and move from selling lamps to selling lighting systems.

Some interviewees highlight that electronic players may enter the market, by exploiting the competencies and the opportunities acquired through the use of LED and OLED technologies for displays. An interviewee highlighted that the lighting industry is more and more intertwined with the videogame one. The collaboration will further develop because the videogame industry needs lighting designers to develop realistic light experiences. Thus, videogames provide inspiring settings to show new lighting opportunities which can be replicated in real contexts. Once LED and OLED technologies will fully develop, the barriers that today limit the

capacity to emulate videogames will be reduced. Finally, the lighting industry is expected to lobby more with the policy level, and this is the result of increasing attention of policy makers towards light as area of energy saving.

The impacts of these complex dynamics in respect to energy saving is hard to estimate from the interviewees (see Table 25). Two trends emerge from the interviews. First, light designers may contribute towards the reduction of energy consumption, because sustainability and energy saving will be part of their education and background. Second, stronger connections with electronics and videogames industries will create new uses and experiences of light that will increase the overall demand. The changes in the value chain and the lobbying activities are more complex to be evaluated.

Table 25 Elements in the light player category

Elements for light players		Feasibility			
Potential for energy saving		Low	Medium	High	Total
	Low	0	0	3	3
	Medium	0	5	2	7
	High	0	2	5	7
	Total	0	7	10	17

Personalized light

This category includes 16 elements, and it is cited by 10 interviewees. It shows a low potential for energy saving and average feasibility. In respect to energy saving, two contrasting dynamics occur in this category. Consumption of light will increase, because personalization of light will be an important factor of new life styles. People will use more light than today, and for more purposes. Lighting will provide new shopping experiences that adapt to the mood of consumers. Similarly, working spaces will use the light to adjust to working tasks. On the other side, light personalization can reduce the use of general light. In both cases, interactivity between technology and (passive) users is a central element.

Table 26 Elements in the personalized light category

Elements for personalized light		Feasibility			
Potential for energy saving		Low	Medium	High	Total
	Low	1	4	1	6
	Medium	0	4	2	6
	High	1	0	3	4
	Total	2	8	6	16

According to the interviewees, personalization of light will contribute to the reduction of useless general light. They also indicate that new life-styles may emerge, but with no clear evaluation about the magnitude of the creation of new demand within the time horizon of the case study.

Daylight

This category includes 13 elements, and it is cited by 10 interviewees. It shows a good potential for energy saving and average feasibility. The potential for energy saving is given by the possibility to replace electric light with natural one. The use of daylight will be more important in new buildings. Windows and other solutions as mirrors and sun tunnels are mentioned by the interviewees. The limitations for energy savings are related to two factors. First, direct sunlight can create thermal problems; therefore the potential for natural lighting is not fully exploited to avoid overheating or overcooling, due to thermal dispersion through openings, especially during cold seasons. Second, daylight can rarely be implemented through retrofitting; therefore it is an important solution but only for new constructions, which represent a small amount of the built stock. The combination of the feasibility and potential dimension confirms the outlook.

Table 27 Elements in the daylight category

Elements for daylight		Feasibility			
Potential for energy saving		Low	Medium	High	Total
	Low	0	0	0	0
	Medium	1	5	0	6
	High	2	1	4	7
	Total	3	6	4	13

Integrated sources

This category includes 10 elements, and it is cited by 8 interviewees. This category and the next ones are mentioned by less than half of the interviewees. Even if our methodology did not explicit account for the number of interviewees mentioning the specific category, such small number may indicate less likeliness of the elements to appear. Anyway, this category shows a medium potential for energy saving and average feasibility. Some Interviewees highlight that the concept of light bulb as we known may disappear. In their view, future lighting scenario will likely appear as an illuminated environment in which any kind of surfaces can become a light source. The concept of light fixture and bulb will disappear. These interviewees mention that displays are already sources of light, even if not recognized as such. In future, thanks to the development of OLED, displays will become more versatile sources of light. Similarly windows are expected to produce electric light when the natural one is not available. The effects of this category on the consumption of energy are unclear, because interviewees think that this category will be develop after 2030.

Table 28 Elements in the integrated sources category

Elements for integrated sources		Feasibility			
Potential for energy saving		Low	Medium	High	Total
	Low	0	2	1	3
	Medium	2	2	2	6
	High	0	0	1	1
	Total	2	4	4	10

Building regulation

This category includes 10 elements, and it is cited by 8 interviewees. It shows a high potential for energy saving and high feasibility. Interviewees indicate that the building code is a powerful tool to incentive energy saving for lighting. Other measures for energy savings are the building certifications (e.g LEED) or the Danish DGNB which assesses the overall performance of a building, among which the environmental sustainability. Only one interviewee highlighted a negative impact of building regulation on energy consumption. In fact, the interviewee mentioned the Danish DS700, the standard for the use of light in building, as a negative example, because building regulations do not often include the state-of-art about technologies and constrains the sector to use sub-optimal solutions to meet the legal requirements.

Table 29 Elements in the building regulation category

Elements for building regulation		Feasibility			
Potential for energy saving		Low	Medium	High	Total
	Low	0	0	1	1
	Medium	0	1	1	2
	High	0	2	5	7
	Total	0	3	7	10

Aesthetic/Emotion

This category includes 8 elements, and it is cited by 6 interviewees. It shows a low potential for energy saving and medium feasibility. This category highlights the emotional role of light. This characteristic is going to increase the consumption of energy for lighting, because people will like to use more light to improve their lighting experience.

Table 30 Elements in the aesthetic/emotion category

Elements for aesthetic/emotion		Feasibility			
Potential for		Low	Medium	High	Total

energy saving	Low	0	4	1	5
	Medium	1	2	0	3
	High	0	0	0	0
	Total	1	6	1	8

Table 30 indicates that such category will not fully develop within the time horizon of the case study, therefore the impacts on energy saving are expected to occur only beyond that time horizon.

Health

This category includes 7 elements, and it is cited by 7 interviewees. It shows a very low potential for energy saving and medium feasibility. In the future, there will be more concern about the health effects of light. Today, there is an increasing knowledge about how light influences human behavior, but this growing body of knowledge is not yet incorporated in many users' decisions about which lighting system to adopt. There is a general consensus that health consideration will reduce the attention towards energy efficiency, because it is expected to be a trade-off between health and energy efficiency in respect to light technologies.

Table 31 Elements in the health category

Elements for health		Feasibility			
Potential for energy saving		Low	Medium	High	Total
	Low	0	4	1	5
	Medium	0	1	1	2
	High	0	0	0	0
	Total	0	5	2	7

Table 31 indicates that such category will not fully develop within the time horizon of the case study, therefore the impacts on energy saving are expected to occur only beyond that time horizon.

Human productivity

This category includes 5 elements, and it is cited by 5 interviewees. It shows a low potential for energy saving and medium feasibility. Three interviewees indicate that awareness about relations between human productivity and light will reduce energy saving efforts, because firms will not consider any more light as a cost, but as a strategy to increase productivity. Consequently, energy efficiency will not be the main criterion of lighting selection in many workplaces. One interviewee thinks that this category will increase energy saving, because it will encourage the replacement of fluorescent tubes with the LED ones. This will happen because light quality of fluorescent technology is very poor. Thus, higher purchasing price will be compensated by the consideration about effects on productivity.

Table 32 Elements in the human productivity category

Elements for human productivity		Feasibility			
Potential for energy saving		Low	Medium	High	Total
	Low	0	1	2	3
	Medium	1	0	0	1
	High	0	1	0	1
	Total	1	2	2	5

Individual control

This category includes 5 elements, and it is cited by 5 interviewees. It shows a high potential for energy saving and high feasibility. This last category includes all the elements in which the lighting user is able to customize its own light. The few elements of this category show that the majority of interviewees consider future light practices as automatized, with few controls from the users. Three interviewees think that individual control will contribute to energy saving, because users can avoid waste of light. Two interviewees have a skeptical position because they highlight that daily routines of users do not maximize the save of energy, as the automatic systems can do.

Table 33 Elements in the individual control category

Elements for individual control		Feasibility			
Potential for energy saving		Low	Medium	High	Total
	Low	0	1	0	1
	Medium	0	0	1	1
	High	1	0	2	3
	Total	1	1	3	5

The network analysis

This section shows the results of the network analysis, which is the analysis of the relations between the different categories. Figure 7 shows the network analysis of the different categories.

Figure 7 The network analysis of the future lighting scenario. Size of nodes represents the total weighted degree. Color of nodes represents the value of betweenness (darker is higher). See Table 34 for network parameters.

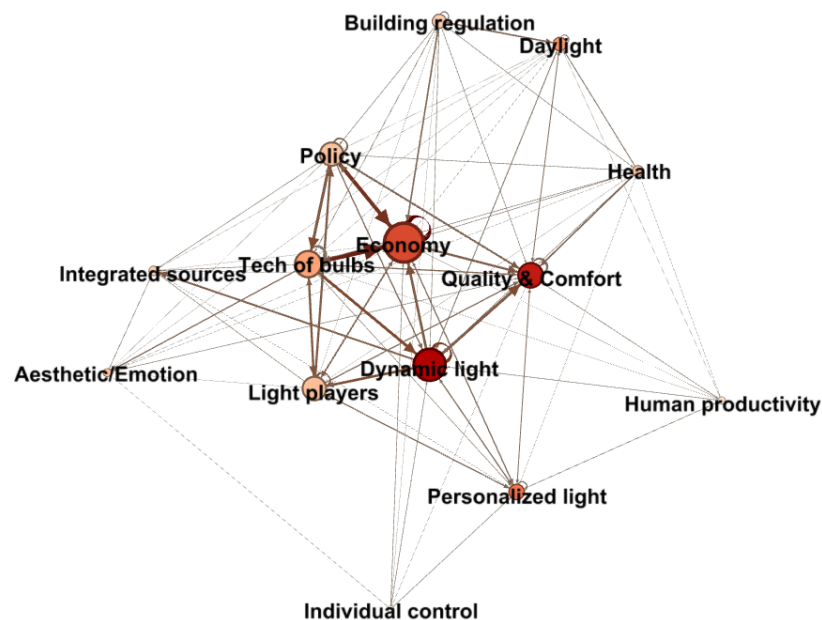


Table 34 reports the main network parameters.

Table 34 Network parameters for the lighting system. Betweenness represents how many times a node is in the shortest patterns between two other nodes. Degree indicates the number of nodes connected to a specific node. Weighted degree indicates the degree value adjusted for the sum of the weights of the edges. For more information see the section about Methodology.

Label	Normalized betweenness	Degree			Weighted Degree		
		In-	Out-	Tot	In	Out	Total
Dynamic light	0.073	13	12	25	53	51	104
Quality & Comfort	0.066	13	12	25	50	28	78
Economy	0.055	14	10	24	77	53	130
Personalized light	0.044	10	9	19	25	19	44
Daylight	0.034	10	9	19	20	17	37
Tech of bulbs	0.030	10	12	22	32	52	84
Light players	0.021	8	11	19	30	44	74
Aesthetic/Emotion	0.018	6	7	13	9	9	18
Policy	0.018	9	11	20	30	43	73
Health	0.017	7	9	16	9	19	28
Building regulation	0.015	9	9	18	16	23	39
Integrated sources	0.015	9	5	14	18	5	23
Human productivity	0.007	4	7	11	6	10	16
Individual control	0.003	5	4	9	5	7	12

Table 35 Rank of the categories according to the different network parameters, from the highest value (1). Talker represents a category with higher out-value than in-value for both degree and weighted degree. Listener represents a category with lower out-value than in-value for both degree and weighted degree.

Label	Betweenness	Degree			Weighted Degree			Role in network
		In-	Out-	Tot	In	Out	Total	
Dynamic light	1	2	1	1	2	3	2	n.a.
Quality & Comfort	2	2	1	1	3	6	4	n.a.
Economy	3	1	3	2	1	1	1	n.a.
Personalized light	4	3	4	5	6	8	7	Listener
Daylight	5	3	4	5	7	9	9	Listener
Tech of bulbs	6	3	1	3	4	2	3	Talker
Light players	7	5	2	5	5	4	5	Talker
Policy	8	4	2	4	5	5	6	n.a.
Aesthetic/Emotion	8	7	5	9	10	11	12	n.a.
Health	9	6	4	7	10	8	10	Talker
Building regulation	10	4	4	6	9	7	8	n.a.
Integrated sources	10	4	6	8	8	13	11	Listener
Human productivity	11	9	5	10	11	10	13	Talker
Individual control	12	8	7	11	12	12	14	n.a.

Table 35 ranks the different categories in respect to the different centrality measures. Dynamic light, quality&control and economy seem the most central category with high value for all the measures (except the weighted out-degree for quality and control).

Economy, technology of bulbs, and dynamic lights are the categories with the most elevated number of outer degree. They are the categories with the most direct influence on other categories. Economy, quality and comfort, and dynamic lights are instead the categories with the most elevated number of inner degree. They are the categories most directly influenced by other categories. In order to understand the overall role of a category in the lighting system, I propose a distinction between *talkers* and *listeners*. Talkers are the category whose outer values outperform the inner ones for both degree and weighted degree measures. Listeners are, vice-versa, the category whose inner values outperform the outer ones for the same two measures.

Among the talkers, there are technology of bulbs, light players, health and human productivity. These categories play the role of sources in the light network. This may indicate that these categories are influenced by external elements to the case study, but they propagate their effects in the case study. In fact, interviewees mentioned the evolution of LED technology as a fact that is going to occur. Along the same line, the evolution of light players follows wider evolutions of technological regimes which cannot be fully understood within the

case study. These aspects seem to confirm that Denmark is a ‘small’ country, as we already highlighted in the background sector, in which long-term dynamics of the lighting sector take place outside its domain and are considered as given.

Among the listeners, there are personalized light, daylight, and integrated sources. These are the categories which are the most influenced by the dynamics of the light network.

The relations between the different elements can be further detailed by investigating the specific most influential and most influenced categories for each category, as in Table 36.

Table 36 Most influential and influenced categories for each category. Percentages indicate the share of the total inner edges (most influential categories) and outer edges (most influenced categories) that connect a category to the other one.

	Most influential categories		Most influenced categories	
1.Aesthetic/Emotion	Technology of bulbs (44,4%)	Daylight, health, integrated sources, light players, policy (11,1%)	Integrated sources, Quality and comfort (22%)	
2.Building regulation	Daylight (25%)	Economy (18,8%)	Daylight, Economy (22%)	
3.Daylight	Building regulation (25%)	Health, quality and comfort (15%)	Building regulation (24%)	Dynamic light, quality and comfort (17,6%)
4.Dynamic light	Dynamic light (20,8%)	Technology of bulbs (17%)	Dynamic light (21,6%)	Quality and comfort (17,6%)
5.Economy	Economy (23,4%)	Technology of bulbs (18,2%)	Economy (34%)	Quality and comfort (13,2%)
6.Health	Building regulation, Technology of bulbs (22,2%)		Quality and comfort (26,3%)	Daylight (15,8%)
7.Human productivity	Personalized light, quality and comfort (33,3%)		Dynamic light, personalized light, quality and comfort (20%)	
8.Individual control	Aesthetic/Emotion, Building regulation, Dynamic light, Economy, Personalized light (20%)		Dynamic light, personalized light, economy (28,6%)	
9.Integrated sources	Dynamic light (33,3%)	Aesthetic/Emotion, Light players, policy, technology of bulbs (11,1%)	Aesthetic/Emotion, Daylight, Dynamic light, Economy, Personalized light (20%)	
10.Light players	Light Players, Technology of bulbs (23,3%)		Dynamic light (18,2%)	Light Players, Policy (15,9%)
11.Personalized light	Dynamic light, economy, light players (16,0%)		Dynamic light, economy, light players, quality and comfort (15,8%)	
12.Policy	Light Players (23,3%)	Economy (20,0%)	Economy (27,3%)	Technology of bulbs (20,5%)
13.Quality & Comfort	Dynamic light (18%)	Economy (14%)	Economy (17,9%)	Dynamic light (14,3%)
14.Tech of bulbs	Policy (28,1%)	Economy (18,8%)	Economy (26,9%)	Dynamic light (17,3%)

The aesthetic/emotional dimension is mainly influenced by the technological development of new lamp. In fact, this confirms that the fluorescent technology today widely used does not allow emotional light, and LED is expected to open new opportunities for light. At the same time, the aesthetic/emotional dimension is expected to push the development of integrated sources of light, and the attention towards quality and comfort.

The building regulation will influence (and be influenced by) the diffusion of daylight and by economy dimension about the cost of lighting and the cost of heating. The daylight dimension confirms the building regulation as the most influential (and influenced) element, showing that these two dimensions are clearly intertwined: building regulation influences daylight practices, new daylight practices and solutions influence building regulation. Furthermore, the daylight dimension is influenced by new knowledge about health effects of light, and increasing attention towards quality of light. Similarly, the daylight dimension is expected to impact the dynamic light concept, because daylight will be integrated in the general lighting management system.

The dynamic light shows wide internal correlations, confirming that it is a complex infrastructure composed by several connected technologies and practices highly dependent on each other. Thus, the development of the dynamic light depends on the development of LED technology, and it will improve the quality of the light system.

The economy dimension shows internal correlations as well, and it shows the role of LED technologies in shaping future economic dynamics, as, for instance, through the delivery of more efficient solutions. Similarly the economy dimension is expected to influence quality and comfort of light. From the interviews, it seems that the relation is negative, because efficiency and cost saving dynamics may reduce the efforts towards better light quality.

The health dimension is pretty influenced by the evolution of new lighting technologies and new building regulations. LED is expected to replace fluorescent technology and this replacement is expected to increase the impact on human health. Current fluorescent tubes are widely considered unhealthy, consequently new technologies will increase such dimension. Similarly, building regulation is expected to increase the health dimension by forcing the use of better electric light and more natural light. The effect of considering health as criterion of designing the lighting system will impact the development of better quality environment, and the use of daylight, as source of natural light with positive effects on well-being.

The human productivity dimension is influenced by the combination of better quality of light and personalized light. As soon as users will be able to exploit better light quality in respect to our specific needs, human productivity is expected to rise as results of improved working environment. Similarly, considerations about the personalization of light will increase the focus on personalized high-quality light. Thus, the analysis reports that this dynamic will influence the development of dynamic light system, as the systemic infrastructure allowing the development of personalized light.

The individual control dimension is widespread connected to several dynamics. Dynamic light and personalized light, as expected, are the two most intertwined elements, showing that the human active interaction is part of a process of personalization of light and of development and use of more flexible and dynamic light systems.

The development of integrated 'bulb-less' light solutions is expected to be possible as long as dynamic light systems will develop, in connections to wider opportunities to enhance the aesthetic experience of light, and LED will play a relevant role as enabling technology. Similarly, the opportunities for developing such innovative light environment will pose some economic issues, and new considerations about how to personalize light.

The development of new light players is connected to the development of LED technologies and the strategy of the light and semiconductor players. This will influence the provision of new light solutions and the policy level, thanks to the lobbying activities that is expected to be exercised by those players. Change in industry is therefore an element that will influence future policies for lighting.

The personalization of lighting solutions is intertwined with dynamic light, economy, and light players. The former will give the infrastructure for personalization of light, and the latter the actors developing it. The analysis shows a strong looping-back system, in which the personalization of light will also call for new light players able to develop dynamic light solutions.

The policy level is expected to influence the pace of development of LED and, because of the lobbying activity previously mentioned, it is also expected to be influenced by the strategies of new lighting players. Thus, the policy level is expected to be intertwined with the economy dimension. In fact, the focus on economic efficiency is a powerful dimension that influences the design of new policies for lighting.

Quality and comfort are intertwined with the development of a dynamic light system and more economic dimension. The connection with dynamic light shows that the concept of quality of light is not simply the development and diffusion of better light, but the capability to develop light systems which adapt to the conditions of the environment, creating the 'right' lighting environment. Similarly, the economy dimension has an important role, because it may become a barrier towards the development of high-quality oriented light systems. In order to overcome such cost issues, it is important that the quality and comfort dimension stresses the positive effects on health and human productivity, previously mentioned.

The technology dimension is influenced by the policy and economy considerations. This result is not expected. From the lighting discourse, we know that efficiency and sustainability have been framed as interconnected elements that play a relevant role in pushing the development and diffusion of LED solutions. The analysis shows that LED will play a role in lowering running cost (and overall costs along the whole life-cycle), and LED will allow the development of the dynamic light concept, as the results of the improved flexibility and versatility of this technology in respect to the fluorescent light.

A focus on energy saving relations

The last part of the results shows the systemic connections between elements with low and high potential for energy saving. Table 37 reports the connections according to the degree of potential for energy saving for both the source and the target elements.

Table 37 Weighted degree according to potential for energy saving

Weighted degree according to potential for energy saving		Target			
		Low	Medium	High	Total
Source	Low	23	26	18	67
	Medium	22	45	39	106
	High	28	60	120	208
	Total	73	131	177	381

There are potential 120 synergies, which are connections between high-high elements. This represents almost one third of the total number of relations. The lighting network is expected to experience several relations between different elements which have a high contribution to energy saving. The actual number of synergies is hard to calculate because the methodology did not highlight the quality of the relation (reinforcing vs weakening).

The group ‘high-low’ includes 28 elements, and it is especially relevant for our research, because it may include some of the potential unexpected negative outcomes of energy saving elements. Given the limited number of occurrences, it is possible to use the audio records to get a better understanding of such relations. We found that, in this group, the technology of bulbs is a source for 12 times, followed by policy (6). Health, aesthetic and quality of light are the most relevant targets. Interviewees highlighted that the technology of bulbs (i.e. the LED technology) will increase the attention towards the health dimension and the aesthetic one, whilst the policy dimension will increase the focus on the development of better quality of light.

The group ‘low-high’ (18 elements) indicates the elements that are not thought to deliver energy saving but that they seem to impact on elements with high energy saving. They may represent the positive ‘paradox’ that is the existence of elements which are not thought to deliver energy saving but they actually do by influencing other elements. Economy (5), health (5), and quality of light (4) are the most important sources of that group. They are expected to impact the development of new LED technology and the building regulation. According to the interviewees, LED technology will be pushed because of its better quality, while the building regulation will be impacted because of health issues related to the use of daylight.

5. Discussion

The discussion part sums up the main results and confronts the main findings of the descriptive and network analyses. The discussion is organized in two sections: i) the first one highlights the main findings of the result section; ii) the second section draws indications about the different contribution of the two concepts of eco-innovations and draws suggestions for policy makers.

Lighting dynamics of energy consumption

All the interviewees indicate that technological development will occur and will contribute to energy saving. Especially LED and the development of a dynamic light system are expected to occur. This finding is consistent with the Danish light discourse, and with overall global evaluations about the potential for energy saving of retrofitting (Lee, 2000; Mahlia et al., 2005) and of the integration of LED in ACS (Leslie et al., 2005; Mohamaddoust et al., 2011). Policies are expected to encourage the diffusion of the LED technology through direct incentives and increase of taxation on energy. Sustainability is indicated as an important driver shaping lighting policies.

Nevertheless, new knowledge about the effects of light on health and human productivity, and more attention towards light and quality, will divert the future attention of lighting actors from energy saving to a more complex set of objectives. Saving energy may turn to be not anymore the priority for the sector, as soon as new objectives will arise in the public agenda. The time horizon of the interviews indicates that technological replacement and policy efforts will take place quickly, while the increasing consideration about the aesthetic dimension, health and integrated light sources will take place over the long term.

Interviewees agreed that LED technology is today driven by the importance of energy efficiency and the political commitment. From the network analysis, it emerges that the evolution and diffusion of this technology is also intertwined with the diffusion of *smart light* systems that is represented by the dynamic light dimension. In fact, dynamic light is the central dimension of the future *smart light* system, because it is the infrastructure that will allow the implementation of new technologies and solutions. There is a general consensus among interviewees that LED and *smart light* are the two elements which, together, can bring relevant energy saving in the provision of light.

However, the *smart LED light* system is described by the interviewees not only as a very efficient technology, but also as superior in respect to many other characteristics (e.g. versatility, dimmability, quality of light) to the current fluorescent light solutions. In fact, the future lighting system will not only arise the efficiency of the lighting system, but also the importance of other dimensions in connection with light such as comfort, aesthetic, health and productivity. As a result, the future *smart LED light* system will open a new world of applications that will be fully exploited only when a new category of market players will take place. In fact, the lighting market is not yet ready to develop the potentiality of these new lighting solutions, because old and new competences need to be integrated in new players, business models, and market solutions.

It is possible to sketch the chronological evolution of these relations. In the short-term, efficiency and sustainability will drive the diffusion of LED technology with important impacts on energy saving. This is showed by the high degree of feasibility given by the interviewees in respect to these dimensions. Meanwhile, interviewees noticed that new knowledge about relation between human and light, and new uses of light will increase the demand for light, but only in a mid-long term. In fact, these dynamics are expected to fully develop only after the diffusion of LED, because the new market opportunities, in order to be fully exploited, will require the diffusion of new market players. Only at that time, new lighting applications will clearly emerge. In that sense, interviewees perceive long-time increase in the demand of light, only when structural

changes will emerge in the market. In respect to energy saving, it is likely that the different time horizon of these dynamics will affect the consumption of energy in two different ways. First, the development of LED will shrink consumption of energy, due to the increased efficiency in the provision of light. Afterwards, the development of new applications and uses of light will arise again the consumption of energy.

The picture indicates a very complex long-term rebound effect, because the expected increase of the demand is not simply the reaction of the demand to the efficiency improvements, but it is also the effect of new potential applications given by LED. These findings recall the ones from Fouquet and Pearson (2006), because they confirm that any lighting revolution may end up in the rise of lighting demand. In conclusion, how the energy saving aspects are specifically occurring and shaped in connection to LED dynamic light will be of central importance for the development of the lighting area in a sustainable direction.

The eco-innovation perspectives and policies

The two forms of eco-innovation gave different findings and policy prescriptions. Through the lens of eco-efficiency, the lighting scenario suggests the need to focus on the development of the LED technology and the *smart light* dynamics. In fact, as confirmed by literature, the future smart LED light system is expected to provide relevant energy savings. In this context, policies that encourage the development and diffusion of LED technology are effective ways to reduce energy consumption, because they counterbalance the development of new lighting practices.

The network analysis indicates the existence of complex relations, because the evolution of the smart light concept based on LED technology will increase attention towards other dimensions than energy saving. Through our methodology, we were not able to detect the magnitude of the potential increase in the provision of light, hence we cannot conclude whether or not the energy saving from improved efficiency will be bigger than the new consumption of energy due to health, human productivity, aesthetic aspects and general comfort. Nevertheless our methodology was able to unveil the existence of these dynamics and the interconnections between them. The result of the network analysis posits important issues for policy makers. Policies that develop and promote new technologies as way to improve efficiency and reduce consumption of energy for lighting shall be carefully designed. This aspect is usually neglected in traditional analysis about the expected benefits of technological changes in the lighting technologies (European Commission, 2012). The birth of the smart light concept will make the light system much more complex than today. Trade-offs between efficiency, health, energy saving and productivity are likely to be evident as soon as LED will develop, new lighting opportunities will arise and further knowledge will be developed. In the future, lighting policies shall choose how to balance these different aims. Shall environmental sustainability still be in the top of the agenda, even when it contradicts with decisions about health and quality of life indicates other patterns? These are complex political decisions which go beyond this study and reside in the domain of politics. Without doubt, there is the need to elaborate more complex evaluative and decisional mechanisms for future light policies, because lighting applications will be more pervasive than today in the human society.

For this reason, we indicate, along the same line of Carrillo et al., that the systemic perspective to eco-innovation represents a superior approach respect to the eco-efficient based one. In fact, some of the major

issues for energy savings highlighted in this paper could not have been detected by only the punctual eco-efficiency form of eco-innovation. The actual advantage of the systemic form of eco-innovation depends on the complexity of the network relations. Complex networks may expect to show more unintended dynamics, especially over the long-term, and especially if policies target only specific elements of the overall network.

6. Conclusions and methodological limitations

The network analysis provides a fruitful approach to understand dynamics of energy consumption for lighting. In fact, the combination of the static and network analyses indicate a complex picture in which many elements interact. We conclude by summarizing the main findings (both for the lighting case and the eco-innovation literature) and by highlighting the main limitations of the analysis.

First, technological development is going to take place and future lighting systems will integrate new technologies in a complex web of relations. Second, policy has the highest potential for energy saving, and sustainability plays a role in shaping the social commitment towards energy saving. Third, LED is not just a more efficient lighting technology, but it is superior in respect to many parameters (quality, customizability, and miniaturization). Fourth, new practices and issues will arise thanks to the new possibilities given by a smart light system based on LED, and that these practices are likely to increase the demand of lighting. Fifth, new players, which integrated new and old capabilities, will enter the market to exploit the potentiality of the future smart LED light system. Sixth, the overall impact on energy consumption will depend on how practices and technologies will be integrated by the future lighting players. Seventh, future policies will face much more complex decision making processes, going beyond the support of new technologies. Eighth, we identified that the eco-efficiency form of eco-innovation was not able to predict future patterns of energy consumption, so we suggest that future eco-innovation studies shall widen their scope and include relationship with consumption patterns, as indicated by Carrillo *et al.* (2010).

We also find indicate some important limitations during the case study. First, edges between elements should have been evaluated also in their qualitative impact, that is a (+) to indicate a positive influence (i.e. the evolution of an element promotes the evolution of another element), or a (-) to indicate a negative influence (i.e. the influence of an element hampers another element). Second, the categorization phase created a subjective bias. A way to reduce such subjectivity would be to use semi-closed interviews, in which elements (i.e. sticky notes) are given to the interviewees. This will solve problem of comparison between interviewees, but it may reduce the capability to unveil new knowledge. Therefore a semi-closed approach shall be anticipated by a consistent pilot test in which the proposed elements are fully validated.

5. Discussion: new conceptualization of eco-innovation

The discussion is organized into three sections. Section 1 recapitulates the lighting development and discusses the dynamics. Section 2 moves the discussion beyond the lighting case and identifies the main conceptual implications of the traditional eco-innovation perspective. Section 3 proposes a new conceptualization of eco-innovation and its main implications for both the lighting sector and the general academic research on eco-innovation.

5.1 The lighting development and the quest for (weak) sustainability

The dynamics of the lighting study have been presented in Articles 1, 3, and 4. Articles 1 and 3 discussed the past dynamics of the lighting development and the associated use of energy, while Articles 3 and 4 forecasted future scenarios and indicated the potential implications of different patterns towards weak and strong sustainability. The present section recapitulates all the main findings of the three articles and provides an overall presentation of the dynamics of lighting.

The history of lighting shows that humanity has been able to develop new lighting technologies that could improve the efficiency of the conversion of energy (watts) into light (lumens). Over the last century, the efficiency of lighting technologies has increased by 1,000 times and these new technologies have become widespread. Gas and oil lamps are no longer used and incandescent bulbs are no longer the most important lighting technology in respect to the quantity of light produced.

Throughout its history, the lighting market has quickly adopted new and more efficient technological lights. Back in the 1920s, incandescent lamps dominated the market. In the 1950s, fluorescent tubes replaced incandescent lamps in the non-residential indoor market. Today, outdoor illumination is mainly provided by highly efficient lighting technologies and the incandescent technology is expected to disappear soon in indoor applications. In fact, from 2015, LED is expected to become the dominant technology. Market mechanisms have not only encouraged the development of more efficient lighting technologies, but they have also quickly diffused them.

Before the 1970s, the adoption of more efficient technologies was not driven by specific environmental aims. Efficiency was framed in terms of reducing operating costs, increasing indoor comfort, and reducing problems in the electric grid. The environmental question arose around the 1970s, due to the oil and energy crisis, and was framed in terms of energy security. It is only since the 1990s that the environmental question has become framed in terms of environmental sustainability. The emergence of the environmental question made the compact fluorescent lamp (CFL) a promising technology, because the incandescent technology was still dominating the residential market. Meanwhile, the increasing importance of the systemic literature about

innovation also influenced policies for lighting. The first policies for the lighting sector, in the 1940s, focused only on antitrust prescriptions. Since the 1990s, however, as the California case has shown, lighting policies have focused on several objectives: increasing awareness of users, encouraging R&D, new skills and knowledge, creating a new niche in the market through public procurement, and increasing competitiveness in an oligopolistic market.

In this context, the environmental question has become an important opportunity for businesses. Lighting players saw the development of more efficient light technologies as a way to encourage the replacement of light bulbs and to achieve public support. Today, many lighting players have identified efficiency is the main reason to replace old but still working light sources with new ones. In fact, they have indicated that the potential cost saving over the whole life-cycle of a lamp suggests shifting to LED technology, even if the purchasing price is superior. Cooperation between policy makers and industry players was considered essential to pave the way for future LED revolution. LED promises new sustainable lighting technologies and is expected to gain an important share of the market from 2015. Therefore, the lighting discourse and dynamics are a good example of the green-growth narrative.

At the beginning of the 20th century, humans were able to convert watts into lumens at a ratio of 0.1 watts per lumen. Today, the best value is around 100 lumens per watt, and the average in Western countries is approximately 60 lumens per watt. Future forecasts indicate that LED will increase its efficiency up to 250 lumens for watt within two decades. The conversion of energy will soon be 2,500 times more efficient than it was at the beginning of 20th century. Humanity is getting closer to the technological limit of 683 lumens per watt that represents 100 percent efficiency of conversion. This value represents an insuperable limit unless new scientific breakthroughs occur. It is worth noting that even if humanity can replace all lighting sources with 100 percent efficient new ones, it would increase the overall efficiency by 10 times compared to current values. Even if these values represent, in absolute value, a relevant increase of efficiency, they are not so impressive if compared to the 1000-fold increase already achieved.

The CFL and LED light technologies have been considered eco-innovations, whilst the incandescent bulb and the first fluorescent tubes did not experience that label. Today any new more efficient lighting technology is labelled as eco-innovation because of its potentiality for increasing energy efficiency. In fact, a CFL bulb *“has a reduced environmental impacts compared to the relevant alternatives”* (Kemp and Foxon, 2007), in which the main alternative was the incandescent bulb. Similarly an LED bulb *“has a reduced environmental impacts compared to the relevant alternatives”* compared to CFL and fluorescent tubes. Using the evaluative criterion of eco-innovation proposed by Kemp and Foxon, even the incandescent bulb was an example of eco-innovation at the beginning of the 20th century, because it had *“a reduced environmental impacts compared to the relevant alternatives”*, represented by the oil and the gas lamps. Similarly the first fluorescent tubes showed the same ‘eco’ attitude by being far more efficient than the traditional incandescent bulb. The history of lighting is of eco-innovations that quickly developed in the market, and future expectations about LED indicate similar patterns.

Nevertheless, the appearance of “eco” dynamics in the history of lighting did not ensure the reduction of the environmental burden in the use of light. In fact, consumption of energy for lighting steadily increased through the 20th century (Fouquet and Pearson, 2006), and the diffusion of LED is not expected to reduce the future consumption of energy for lighting (Tsao et al., 2010). As Tsao et al. suggested, the rebound effect for lighting is very consistent – nearly 100 percent – and *“No empirical evidence is found for a saturation in per-capita consumption of light, even in contemporary developed nations”* (Tsao and Waide, 2010, p. 259). The case study proposed in Article 4 seems to provide qualitative proof of this statement. In fact, experts indicated that LED is not only a more efficient technological replacement for fluorescent tubes, but is also widely recognized as being superior in respect to quality, customization, and versatility. LED technology is expected to open up new possibilities in the use of light (such as integration of light sources in other materials). The development of these new opportunities in the provision of light will depend on the development of new market structures and players. Light designers will be important future players because they will have knowledge about designing complex light systems. Similarly, new lighting players will come from the semiconductor industry, developing new typologies of services and solutions. Light will no longer be used just to illuminate, but also to provide new sensorial experiences. Shopping centers and working places are expected to develop new lighting solutions that will improve consumers’ shopping experiences and workers’ productivity. The diffusion of LED will be intertwined with the increased knowledge about human health, well-being, and comfort. As result, the performances of the light systems will no longer be evaluated only in terms of lumens and watts, but will include a range of complex performances. Consequently, increasing energy efficiency will no longer be the only criterion of evaluation of new lighting technologies and solutions. Such change in the evaluative criteria may lower the pace of development of efficiency for future innovations. Through my case study, I identified and analyzed some of these dynamics. Researchers and experts agree that these dynamics are likely to increase the demand of lighting, and to reduce the importance of energy saving in users’ future choices about light.

Therefore, labelling the LED as an “eco” innovation because it *“has a reduced environmental impacts compared to the relevant alternatives”* is reductive and myopic. It is reductive because LED should be understood as a superior technology with many underestimated consequences, and it is myopic because this new technology will generate new practices that are still not fully understood. Consequently, the actual impacts of LED in terms of energy consumption may be different from the pure evaluation of energy efficiency. For that reason, a weak sustainability perspective cannot ensure the improvements of strong sustainability. Similar dynamics seem to be occurring now as in history, which makes it important that new conceptualizations of eco-innovation are not left out when considering the overall impacts on lighting practices. For that reason, the definition of LED as an eco-innovation deserves more analysis and understanding.

5.2 Eco-innovation for weak and strong sustainability

This section starts the discussion beyond the lighting case study and concludes by referring back to it, in order to show that the dynamics in the lighting sector can be considered as part of general patterns occurring in the society about the dynamics of eco-innovation in respect to sustainability. These aspects have been analyzed mainly in Articles 2 and 3. Article 3 provided an overview of the societal discourses about eco-innovation and

sustainability. Article 2 focused on how these discourses (and, more exactly, the terminology) took place within the academic community.

Article 3 has identified the existence of six different narratives of sustainability, linking the relations between different typologies of innovation (non-eco, eco-efficiency, systemic) with the final impact on demand (increasing vs. decreasing). The attention given to discourse and language was mainly driven by the consideration that the use of language is a form through which societal actors influence the course of innovation, thanks to the evaluative power that societies carry.

One of the main findings was that the society is in the middle of a *narrative transition* from a *business-as-usual* narrative to a *green growth* narrative, and that the *relative decoupling* narrative is an essential turning point with which to understand such passage. The relative decoupling narratives had their roots in the weak sustainable perspective. Essentially, the relative decoupling narrative suggests that societies shall aim to increase the ability to delink economic growth from consumption of environmental resources. This is the essence of the weak sustainable perspective. In the last decade, the birth of the green growth narrative made this link even stronger. The *green growth* narrative indicates positive feedback between economic growth and environmental sustainability. There is a strong normative value here: thanks to efficiency, economic growth entails environmental protection; thanks to efficiency, environmental protection entails economic growth. The example of the environmental curve of Kuznets is paradigmatic, because only richer societies can deal with certain important environmental issues. Therefore, being poor is unsustainable (Martínez-Alier, 1995). The *green growth* narrative is an extreme evolution of the relative decoupling one. In the *relative decoupling* narrative, economic growth and environmental protection can co-exist. In the *green growth* narrative, however, economic growth and environmental protection are mutually dependent. Consequently, society and especially policy makers are called to encourage both economic growth and environmental sustainability *at the same time* through innovation and efficiency. Policy makers are expected to create the proper framework conditions (that is, the systemic conditions) that encourage cooperation between the different societal actors. Cooperation is suggested because the 'win-win' concept indicates that all the actors will benefit from innovation and cooperation. Ultimately, societies that are able to do that will end up being richer and greener.

The bibliometric analysis, proposed in Article 2, analyzed the evolution of the peer-reviewed literature about eco-innovation. The comparison of those findings with the different narratives proposed by Article 3 can provide further understanding about the evolution of the eco-innovation concepts among academics in the last two decades. Article 3 indicated that the passage from the non-eco form of innovation to the eco form was a consequence of the sustainable development concept in the 1980s and 1990s. Article 2 confirmed such dynamics, highlighting that from the 1990s onward, there has been an increasing use of such prefixes as 'eco', 'green', 'environmental' or 'sustainable' in connection with the innovation literature. The differences between these prefixes could be anchored to the different narratives. Indeed, patterns of popularity and meanings of "eco", "enviro-", and "green" show consistency with the dominant narrative transition from the *business-as-usual* narrative to a *green growth* one. In fact, "eco" showed a focus on the diffusion of innovations and their impacts on (green) growth, and on the development of environmental friendly products and services. The "enviro-" and "green" prefixes showed connections with the work of Porter on the relations between

environmental standard and competitiveness, and on the determinants of innovation at the firm and industry levels.

The different course of “sustainable” innovation is also consistent with the different evolution of the six narratives. “Sustainable” innovation seemed less popular and more connected to the behavioral implications of sustainability, and to the wide transition of complex socio-technical systems. Thus, “sustainable” innovation showed a high degree of isolation in respect to references and authors. This dynamic is consistent with the narratives of *absolute decoupling* and *techno-thrift*, which call for complex socio-technical changes towards sustainability, for which practices and routines are an essential element.

The bibliometric analysis seemed to confirm the overall findings of the general discourse about eco-innovation and sustainability. Similarly, as the previous section showed, the lighting dynamics show a *narrative transition* from a *business-as-usual* narrative to a *green growth* narrative. As long as societies aim to improve weak sustainability, societies develop eco-innovations that decouple the demands of light from the consumption of energy. Since these eco-innovations need to be profitable, policy makers and industry players shall find new market opportunities that represent the incentive to the development and diffusion of these innovations. In this way, it is possible to increase economic growth and decouple it from energy consumption. Today, important lighting industry players are engaged in developing and diffusing new lighting technologies that increase the efficiency in the provision of light. Similarly, policy makers expect new lighting technologies to contribute to shrink the consumption of energy for lighting. Consequently, all the actors welcome the most recent market scenarios, which indicate 2015 as a turning point, from which LED will increase its market share and become the dominant technology within a few years. At the same time, all these players foresee new applications for lighting in both developed and under-developed countries that expect to open new markets and market opportunities.

Overall, the articles in this thesis and the present discussion show that societies are living in the middle of a transition towards a green growth perspective. Since this model relies heavily on increasing demand to solve environmental problems, I believe a conceptual clarification of the relations between eco-innovation and sustainability is urgently required in order to provide more clarity about the expected future patterns of sustainability. For that reason, the next section presents the different conceptualizations of eco-innovation and their connections with weak and strong sustainability.

5.3 The new conceptualization of eco-innovation

This section reflects the main contribution to the eco-innovation debate, and presents major implications for policy makers, the lighting case, and research. These findings have been partially discussed in the articles, especially Article 3. However some of findings are novel to the articles because they have been formulated by combining the four articles in the thesis. This section is organized into four parts. The first part presents two different conceptualizations of eco-innovation, which represent the case of eco-innovation for weak sustainability, and the case of eco-innovation for strong sustainability. For the sake of simplicity, I have labeled the former as “weak eco-innovation” and the latter as “strong eco-innovation”. The main discussion will lead to

three specific parts in which the novel conceptualizations are analyzed in respect of the implications for general policy makers, and the specific of the lighting study. The last part indicates how future eco-innovation literature can be further developed by integrating the other literature used in this thesis.

The proposed conceptualization of strong eco-innovation is thought to link innovations and practices to the level of society. Whenever societies become interest in preserving a specific asset of natural capital (for example, limiting CO₂ concentration in the air), a coherent conceptualization of the relations between eco-innovation and sustainability is needed. Table 38 summarizes the relations between innovation and weak and strong sustainability.

Table 38 Relations between innovation and sustainability

Relations between innovation and sustainability		Is this type of innovation “eco” according to...	
		Weak sustainability?	Strong sustainability?
Effect of innovation	Increase efficiency	Yes	Depends on the rebound effect
	Reduce consumption	No	Yes

I propose the following definition of strong eco-innovation: *“An eco-innovation is any kind of innovation that diffuses new practices that reduce the environmental impacts of society.”* Table 39 compares the weak definition, as proposed by Kemp and Pearson, with the strong one I propose.

Table 39 Definitions of eco-innovation

Weak eco-innovation	Strong eco-innovation
An eco-innovation is any kind of innovation that has a reduced environmental impact compared to the relevant alternatives.	An eco-innovation is any kind of innovation that diffuses new practices that reduce the environmental impacts of society.

According to weak definition of eco-innovation, it is the innovation that is expected to reduce environmental impacts. According to the strong one, it is the society that it is expected to do so. In this last definition, the focus is on society and the new practices that are formed when innovations diffuse. Such practices can reduce or increment the environmental burden of the society, and efficiency is just one of the factors that influence it. The lighting case provided several examples. The incandescent filament was a weak eco-innovation, but not strong; the difference depended on the new demand for lighting that was encouraged by this new technology. Traditional oil and gas sources were unhealthy, especially for indoor applications, were not versatile, and were complex to be provided. For that reason, even if the incandescent technology was “greener” than traditional technologies, its applications increased dramatically the energy demand for lighting.

Table 40 Summaries of the relations between eco-innovation and sustainability

Vision of sustainability	Criterion of sustainability	Eco-innovation definition	Locus of sustainability
Weak sustainability	Decoupling economic growth from environmental impacts	An eco-innovation is any kind of innovation that has a reduced environmental impact compared to the relevant alternatives.	Performances of innovation
Strong sustainability	Preserving natural capital	An eco-innovation is any kind of innovation that diffuses new practices that reduce the environmental impacts of society.	Practices of society

The possibility to use weak sustainability as a proxy for strong sustainability depends on the elasticity of the production and consumption curves. If demand reacts slowly to the change of efficiency, weak sustainability is expected to improve strong sustainability. If demand is highly influenced by elasticity, improvement of weak sustainability may not assure improvement of strong sustainability. Elasticity indicates how production and demand are linked to specific factors (such as price). Elasticity means that demand and production are not rigid, but do respond to external stimuli.

The consideration of elasticity helps to unveil a counter-intuitive case of eco-innovation; that is, when dirtier technologies (than the relevant alternatives) may improve environmental sustainability. This is possible if less efficient innovations change practices in the society in a way that has the overall effect of reducing environmental burden. By way of example, if we would hypothetically switch back to oil lamp technology in our houses and, we would probably reduce our use of light to the essential needs. We may end up in a world that consumes less energy for lighting, because of an inconvenient, less flexible, and more polluting technology. Table 41 represents the different definitions of weak and strong eco-innovation in connection to innovations that modify efficiency and demand.

Table 41 Four cases based on potential combinations of efficiency and consumption in connection to strong eco-innovation

Relations between strong eco-innovation, efficiency, and demand		Impacts on the final usage (e.g., demand for light)	
		Less demand	More demand
Effect of innovation on efficiency	Increasing efficiency	1. Weak and strong eco-innovation	2. Weak eco-innovation, and possible strong eco-innovation
	Decreasing efficiency	3. Possible strong eco-innovation	4. No eco-innovation

Case 1 represents the “normal” notion of eco-innovation: a greener technology that results in improved environmental performances of the society. I will not discuss this scenario further as it has already been widely developed in the common wisdom about eco-innovation. Cases 2 and 3 are much more interesting because they show the differences between the traditional and proposed eco-innovation perspective.

Case 2 represents the paradox whereby a more efficient innovation generates new final demand. This was the case of the incandescent lamp. This scenario represents a weak eco-innovation, because the proposed innovation (for example, a more efficient car engine) is more efficient than the relevant alternatives (a less efficient car engine). This case may or may not represent a strong eco-innovation, because three options are possible:

1. Option A. The overall demand for the resource being used more efficiently is reduced because the increased environmental benefits of more efficiency are superior in respect to the increase of the demand generated by the innovation. This is a case of strong eco-innovation, even if the magnitude of the environmental benefits is inferior to those claimed by the specific performance of the innovation.
2. Option B. The overall demand of the resource being used more efficiently is increased because the environmental benefits of more efficiency are inferior in respect to the increase of the demand generated by the innovation. This is not a case of strong eco-innovation.
3. Option C. The overall demand of the resource being used more efficiently is stable because the environmental benefits of more efficiency are exactly offset by the increase of the demand generated by the innovation. This is a case of neutral innovation.

General speaking, all these options are weak eco-innovations, but only option A is a strong one. Options B and C are examples of the paradox, because they represent weak eco-innovations that do not improve strong sustainability (but they may nonetheless be pursued for non-environmental reasons).

Case 3 represents a less efficient technology (in respect to the relevant alternatives) that helps reduce the final demand. This scenario is similar to the case 2, meaning that three options are possible:

1. Option A. The overall demand of the resource being used less efficiently is reduced because the loss of efficiency is inferior to the reduced demand caused by the innovation. This is a case of strong eco-innovation.
2. Option B. The overall demand of the resource being used less efficiently is increased because the loss of efficiency is greater than the reduction in demand caused by the innovation. This is not a case of strong eco-innovation.
3. Option C. The overall demand of the resource being used less efficiently is stable because the loss of efficiency is exactly compensated for by the shrink of the demand caused by the innovation. This is a case of neutral eco-innovation.

Case 3 does not represent weak eco-innovations, but option A does represent a case of strong eco-innovation. This case may be label as the “positive” paradox, which, as far as I can ascertain, is not mentioned in the literature. The question of whether or not such innovations are pursued is part of a normative discussion that I briefly sketched later in the section about implication for policy makers. Nevertheless, I argue that the dominant weak perspective has implied that this possibility of eco-innovation has not even been considered in the literature. For example, an incandescent bulb would never been defined as “eco” in respect to the LED one, because of its inferior energy performance. In this scenario, this technology may be “eco” if it generates practices that result in reduced energy demand for lighting.

When strong sustainability is debated, the proposed formulation of strong eco-innovation has two benefits in respect to the weak one. First, it is able to detect the paradox discussed in the literature (case 2, options B and C). Second, it is able to show new potential strong eco-innovations (case 3, option A) that would not have been even considered as such. This second benefit provides new opportunities to identify strategies to promote strong sustainability, even if this may pose several normative issues, as I will discuss in the next section.

Generally speaking, the ability to obtain different results from the traditional definition depends on the acknowledgement of the relations between consumption and production; that is, the inclusion of elasticity at the micro-level, or the rebound effect at the societal level. If elasticity is zero (demand does not rebound when the production curve changes), the traditional and the proposed definitions provide the same results. In other words, weak and strong sustainability dynamics match when elasticity is zero.

5.3.1 Implications for policy makers

Politics and society should discuss which type of sustainability should be pursued because of the important normative repercussions (Cattaneo et al., 2012). At first glance, the weak sustainability, as framed by the *green growth* narrative, does not pose relevant normative issues because it indicates benefits for the whole society and it reflects the current distribution of powers among the different actors. Why should we limit consumption for environment when it is possible to have both? In fact, the weak eco-innovation perspective provides a much more optimistic view about the future. Humanity has proved that it is able to develop new technologies and increase the efficient use of scarce resources. Consequently, the weak eco-innovation discourse relies on further developing a capability that we already have: to increase human-made capital. The result is that society will try to develop a techno-optimistic future in which humanity will master new knowledge and technologies and, by definition, solve environmental problems. We can even predict that this scenario could end up in the extreme case of a dematerialized economy or in a science fiction case in which we will ruin our planet but are able to live on other planets. In fact, knowledge may be expanded up to the level in which humanity can master the entire universe as a form of natural capital. In this scenario, policy makers should evaluate innovations only according to their ability to increase the total amount of natural and human-made capital. Since it is very hard to quantify and evaluate the variation of natural and human-made capital, the most pragmatic choice is to target the efficiency of the economy as the main proxy of weak sustainability. Consequently, policy makers should pursue any kind of innovations that can improve the efficiency of our economy and, consequently, improve the overall amount of capital. Degradation of natural capital will be compensated by an increase of artificial capital.

At first glance, the strong sustainability implies an important normative issue, because it implies policies that assure the conservation of a certain amount of natural capital. Such policies will target the consumption side and will allow economic growth only at the extent to which it does not increase the consumption of natural capital over such a threshold. Western societies have never dealt with limits, so these policies may impact current lifestyles and freedom of choice. Some scholars have even accused the degrowth positions of “eco-fascism” (Friedman, 2006; Muraca, 2012; Tukker et al., 2008). In fact, even if the use of standards or limitations on specific technologies (such as bans on incandescent bulbs) and practices (such as the pedestrianization of an

urban center) have faced only minor normative criticisms, the idea of managing the overall consumption of resources does have some harsh critics, because it is considered a limitation of human freedom.

This normative analysis relies on the idea that weak sustainability implies strong sustainability. If this assumption is removed, weak sustainability implies normative considerations about the distribution of the effects of ruining the natural capital, in connection with the different distribution of human-made capital between different societies. As I have argued, policy makers should be aware that a weak sustainable pattern does not ensure the preservation of natural capital. Therefore, eco-innovations that do not reduce energy consumption should be accepted as the expected consequences of this approach. This position has made the normative discussion more complex. On the one hand, the strong sustainability still implies considerations about sovereignty and freedom of consumers. On the other hand, weak sustainability implies a transfer of negative effects from wealthy societies (or social groups) to poor ones. Indeed, only wealthy countries (social groups) have the needed human-made capital to afford a reduction in the natural one. Countries that are not able to do this will suffer a net decrease in the sum of their natural and human-made capitals. For instance, this is the case of food or water scarcity in many poor parts of the world due to climate changes provoked by wealthy societies. In fact, poor societies are not able to fully develop the adaptation policies that are required to live in a weak sustainable perspective. In my view, the strong sustainable approach is fairer than the weak one because it discusses the limits within the communities that generate the negative environmental impacts. Instead, the weak perspective transfers the negative impacts onto the poorest ones, which are not able to cope with them. In my view, it is better to limit the sovereignty of who create the problems (that is, the consumers) than to starve the rest of the world.

Independently from my personal position, the most important finding of this section is to highlight the point that both the eco-innovation approaches to weak and strong sustainability imply the need for normative discussion and choices. I found the actual optimistic message carried by the green growth narrative to be quite dangerous. According to this narrative, everyone is expected to benefit, which implies that there is no need to address the normative aspects of such a model of development.

The normative dimension implies that the innovative process shall be shaped towards sustainability, as Hekkert *et al.* indicated in their introduction. The majority of the eco-innovation literature does not consider the environmental motivation of the innovative process to be relevant, even if it is acknowledged that it may ease the design of eco-innovations (Carrillo-Hermosilla *et al.*, 2010; Könnölä *et al.*, 2008; Pearson and Kemp, 2007). The proposed strong eco-innovation definition slightly differs from that view, because it indicates that motivation is an important factor in shaping new practices and routines (Mannetti *et al.*, 2004), which are rooted in the normative values that drive the individuals' behaviors. Consequently, policy makers should also pursue sustainability in society in terms of environmental consciousness, because doing so may help shape new practices that reduce the environmental burden. The life of Thomas Edison was an extreme metaphor for the role of motivation. Edison's commitment was to banish darkness from human society in order to improve

human well-being.¹⁶ In his view, darkness and sleep were the two dimensions that hampered the development of human beings. When he invented the incandescent lamp, he hoped that such technology could help humanity to illuminate everything at any time. If we expect practices to follow motivations, then incandescent technology would surely not have been believed to reduce environmental impacts in the use of lighting.

5.3.2 Implications for the lighting case study

As I have already claimed, the lighting discourse is in the midst of a *narrative transition* from a *business-as-usual* narrative to a *green growth* one. Thus, I have argued that this transition may not ensure the reduction in the consumption of energy for lighting because the efficiency is reaching the technological limit of 683 lumens/W, and there is still an important demand for light that is expected to develop once new applications develop in the market. Therefore, this thesis argues that the lighting discourse shall move from the *relative decoupling* narrative to the *absolute decoupling* one or, in a more systemic way, from the *green growth* narrative to the *techno-thrift* one. This section indicates how this passage will implicate new policies and practices that may pursue such transition.

Following the same structure of Article 3, the proposals, which have been discussed in Article 3 and 4, are divided into the four following categories: business models, policy and society, taxation, and technology. The common element among all of these categories is that they may be able to activate virtuoso practices that can control the future increasing demand of lighting.

Business models. Business models represent the rational of firms' behaviors. As long as business models encourage the sale of lumens, new opportunities emerging from efficiency may be used to incentivize the production of more lighting. For that reason, the traditional lighting business models, based on the sale of lamps, are ineffective at encouraging the control of demand. For that reason, Article 3 proposed a category of lighting service company (LISCO) that aims to sell useful illumination and pays for the electricity. LISCO companies will get paid according to the quantity and quality of lux they are able to provide for specific visual tasks. Visual tasks require a specific amount of lux and a specific color quality. Any excess in the production of lux shall not be counted because it represents useless production of light. Similarly, the quality of light shall be part of the evaluation of the service. The idea was partially inspired by the example of a Dutch company that retrofits offices with daylight openings and gets paid based on the quantity of lumens/hours produced by these daylight openings.

Policy and society. This aspect includes the behaviors of policy makers and users. The first proposal is that policy makers shall track the demand for lighting. Data sometimes indicates the lumens/hours, which is the real measure of the demand for light, while the measure of watt/hours, which is not a measure of demand for lighting, is often reported. Data about demand for lighting would increase awareness about the astonishing

¹⁶ Edison once stated “When I went through Switzerland in a motor-car, so that I could visit little towns and villages, I noted the effect of artificial light on the inhabitants. Where water power and electric light had been developed, everyone seemed normally intelligent. Where these appliances did not exist, and the natives went to bed with the chickens, staying there until daylight, they were far less intelligent” (as cited in Coren, 1997, p. 2).

augmentation of the consumption of lighting. Second, policy makers may promote a new energy label for building that includes lighting performances. Currently, only a few non-experts are able to evaluate the quality and the quantity of a light required from a new building. The light quality of a building shall be reported in a specific label that assesses the need of artificial and the quality of the natural light for each room or space. Third, policy makers should recognize that the actual sectorial boundaries of lighting frame the lighting sector as the field of the electric bulb. This is only a partial interpretation of the lighting dynamics, because natural lighting is also an important source of light. New lighting organizations shall include all the players, as windows producers, that are involved in the provision of light. Fourth, policy makers seldom consider lighting pollution to be a relevant issue. More awareness about this phenomenon may help to delink the equation that more light always means more well-being and wealth.

Taxation. Energy taxation shall change to offset the expected cost saving due to increase of efficiency in lighting technologies. More precisely, a pattern of increase in the energy taxation shall be defined ex-ante according to the expected increase of efficiency in the lighting sector. In that way, innovation and diffusion of more efficient lighting technologies are still encouraged. A more complex taxation system, which requires the development of the *smart* light concept, may differentiate between the taxation of useful lux (that is, the taxation of lux that allow visual tasks) and the taxation of useless lux (that is, the taxation of lux that are not needed to perform visual tasks), where the latter should be taxed more.

Technology. Future light is expected to be *smart*, thanks to the integration of LED technology with advanced ACS and communication systems. In the future, smart light shall be developed to identify the differences between useful light (that is, light that allows visual tasks) and useless light (that is, when visual tasks are not performed). This is possible through a high personalization of the provision of light that adapts to the condition of the (lighting) environment and the visual tasks to be performed. LED should be fully exploited in its versatility and miniaturization, two characteristics that were missing in the fluorescent light. Future smart lighting systems shall widely integrate natural lighting sources and consider them as part of the overall lighting settings. Therefore, new technologies that convey sun beams, as optic fibers, shall be further integrated in the design of lighting systems, in order to provide natural light even where windows are not present.

The above-mentioned proposals can be further developed and analyzed, as can their potential drawbacks. For example, as suggested in Article 4, wider integration of daylight may provide thermal issues that can require more electricity for cooling/heating systems. It is beyond the scope of this thesis to evaluate the optimal design for integrating different solutions. In fact, my purpose was to show that there are some proposals that can explicitly reduce the demand of artificial light and/or energy for light. Demand-oriented measures do not simply suggest a cap on the overall demand, because they may also be designed to promote practices that reduce the demand. This concept is often neglected by the detractors of strong sustainability, because it is not true that this approach always implies measures that limit consumers' freedom.

Through the lenses of demand-side measures, further considerations can be made in relation to the historical evolution of lighting technologies. The incandescent technology is much more versatile than the fluorescent one in at least three aspects: (1) Incandescent lamps can easily be dimmed; (2) they have a very quick on/off

cycle; and (3) even intensive dimming and switching on/off do not reduce their duration and quality of light. Consequently, the incandescent technology could have been easily integrated in ACS, with important potentiality of energy saving. For example, modern offices use 24-hour-on fluorescent lamps, even in areas that are seldom used during the day (such as bathrooms). In that case, a deep integration of incandescent lamp with ACS may provide interesting potentiality of energy saving. In my view, the lack of development of ACS systems in recent decades was not only due to certain technological limitations (for example, wireless communications were not available), but also partly due to the evaluative power of society. Since the incandescent bulb was not thought to save energy, potential energy saving applications were not developed. Similarly, since the main business model of the sector was the sale of lamps, fluorescent lamps were seen (as shown in Article 1) as a way to increase the overall sale of lamps, not to substitute for incandescent ones.

The main conclusion of this part is that a technology can be used in different ways; that is, different practices can be developed around new technologies. Therefore, it is difficult to analyze the “eco” dimension solely by looking at the specific performance of the technology. Similarly, LED will become an eco-innovation only if it pursues the development of lighting practices that increase efficiency and reduce the demand for lighting (or at least of energy for light). If LED pursues new ways of thinking about lighting systems and new business models that do not reward only efficiency and sale of lamps, this technology will truly be “eco”. The evolution of LED through these patterns will depend on the systemic conditions that will surround this technology. Therefore, if the aim of societies and policy makers is to preserve the natural environment, they must activate mechanisms that will move the lighting discourse towards more strong sustainable patterns.

5.3.3 Implications for research

The quality of the eco-innovation research can greatly be improved through different strategies. The first requires a deeper integration with the indicator for sustainability literature. For example, Horbach (2005) identified three levels of indicators for sustainable development: (1) Determinants of sustainable innovation, (2) description of the innovation; and (3) ecological, economic, and social impacts. The different positions between the definitions of Kemp and Foxon, and that of Hekkert et al., can be understood by looking at the different role of the indicators regarding the determinants of sustainable innovation. For Kemp and Foxon, the current determinants provide the right set of incentives, because increasing efficiency is a relevant force of the innovative process. For Hekkert et al., the need for guidance of innovation reflects the need to change the determinants of the innovative process. More generally, it is important to acknowledge that different definitions of eco-innovations shall be tracked through very different indicators. For example, the definition of eco-innovations as *“Innovations which are able to attract green rents on the market”* (MM Andersen, 2008) shows a focus on business indicators that differs greatly from other more environmental-based definitions, as *“Eco-innovations are all measures ... which contribute to a reduction of environmental burdens or to ecologically specified sustainability targets”* (Rennings, 2000). Overall, the suggestion is to systemically integrate the sustainability literature, which can provide the normative frameworks that can help define the criteria and the indicators through which innovations are assessed as “eco” (Ayres, 2008; M. Pansera, 2012; Smith et al., 2010). Surprisingly, the weak/strong sustainability is seldom mentioned explicitly in the eco-innovation definitions, which creates conceptual obscurity about the expected benefits of any innovations. By clearing the normative value through which society builds expectations about innovations, the eco-innovation

analysis can improve its capacity to respond to actual societal needs, and develop and use the most appropriate set of indicators, as proposed by Rennings and Hohmeyer (1999).

The second and connected strategy suggests integrating the rebound effect literature, which can help the eco-innovation literature assess the effects on consumption of any innovation. The current systemic effort of many eco-innovation approaches focuses on fostering the innovative process itself. I would label that approach as “the systemic approach to the production of innovations.” The sustainability transition literature (Geels and Schot, 2007; Geels, 2011; Marletto, 2014; Rotmans et al., 2001) is an example of a theoretical approach that highlights the wide societal dynamics, but has not yet been included in the discussion about the definition of eco-innovation within that literature. The importance of integrating the rebound effect literature or, more generally, the interplay between practices and innovations, arises only when strong sustainability is discussed. Joseph Schumpeter, the father of the innovation studies, sketched a mark III (or mark SC) model in which he proposed to understand innovation in its wider interactions with economy, science, family (that is, society) and policy (E.S. Andersen, 2012). Andersen concluded that “*it seems important to start developing a family of ... [Schumpeterian] models that include the impact of the natural environmental on economic evolution, and vice versa.... But ultimately these models have in some way to deal with the complexities of socio-economic coevolution*” (E.S. Andersen, 2012, p. 28). In my view, the rebound effect literature and the sustainable literature provide direction for such efforts to develop more complex socio-economic eco-innovation analyses. Similarly, Smith et al. (2010) indicated the need to widen the perspective on innovation studies by addressing the normative dimension of innovation.

The conceptual weaknesses of the eco-definition suggest the need to integrate the philosophical discussion about environment and human beings. Consequently, my thesis calls for a more cooperation between technical and non-technical fields of research, because of the fundamental contribution given by the humanistic sciences in defining the future societies we are aiming at. Such normative discussion is seldom present in the eco-innovation debate, where the technical dimension seems dominant. Along this direction, the socio-technical analysis (Bijker and Law, 1994; Bijker, 1997) can provide useful insights into the eco-innovation discussion.

6. Conclusion

This thesis started with an acknowledgment of a paradox between technology development and innovation, discussed in the eco-innovation literature. The aim of the thesis has been to contribute to that debate by framing a new eco-innovation perspective in which such paradoxes can be properly understood.

The thesis has introduced three streams of literature, the interconnections of which can provide a conceptual framework to clarify the ontology of the paradox. The first stream reported the complexity of the eco-innovation literature and emphasized the differences among scholars in understanding the relations between environment and innovation. Such difference has generated conceptual complexity about the essence of eco-innovation. The second stream reported the sustainability literature; that is, the literature regarding the existence of the physical dimension of economy and its connection with the concept of limits. In that section, I emphasized that two very different visions emerged (weak vs. strong sustainability) and that a main focus of that debate was the relation between technology and environment. Advocates of weak sustainability indicate that sustainability depends on the combination of natural and human-made capitals; therefore, sustainability depends on the efficient conversion of natural capital in the human-made one. Advocators of strong sustainability indicate the need to preserve a critical amount of natural capital; therefore, sustainability depends on measures that conserve such capital. The third and final stream reported the rebound effect literature; that is, the literature about the relations between efficiency and consumption. In that section, I emphasized that, for some studies, the rebound effect can be significant; consequently, increasing efficiency is not a strategy to reduce consumption. For others, the rebound effect seems marginal and, therefore, increasing efficiency is a strategy to reduce consumption.

Four articles provided the main analysis and findings for the discussion. Article 1 focused on the lighting sector and provided an overview of the historical evolution of lighting technologies during the 20th century. The article showed that the lighting sector has significantly increased the efficiency of the conversion of energy in lighting through a strong incremental innovative pattern that led to the development and diffusion of three different lighting technologies: the incandescent, the fluorescent, and the LED semiconductor.

Article 2 studied the evolution of the academic literature about the relation between innovation and sustainability, looking at the diffusion of four different terminologies of eco-innovation (*eco-innovation*, *environmental innovation*, *green innovation*, and *sustainable innovation*). Results indicated an increase interest towards the topic, and the existence of a connection between the different terms and different scientific communities which carry different positions, interests, and visions about the eco-innovation concept. In fact, *sustainable innovation* is more focused on the behavioral implications of sustainability, and the transition of complex socio-technical systems. *Eco-innovation* focuses on the design and diffusion of environmental friendly. *Environmental innovation* focuses on the relations between firms, competitions and policies. *Green innovation* is the Asiatic variant of *environmental innovation*.

Article 3 is the central proposition of the thesis. It identified six narratives about the relation between innovation and consumption and proposed a framework through which the narratives are compared in respect

to sustainability. The framework has been applied to analyze the narratives in the dynamics in the provision of light. The case study indicated that the dominant narrative about sustainability combines an effort to accelerate the innovative process with an increase in the demand for light. Article 3 warned about the feasibility of this narrative in achieving long-term reduction of energy consumption for light, and concluded by proposing some new practices that could both increase the efficiency of lighting technologies and control the overall demand of light, leading to a net reduction in the consumption of energy.

Article 4 interviewed Danish experts about their forecasts for future dynamics in the use of light and their assessments of the associated consumption of energy. The results suggested that the future lighting system will be *smart* and *efficient*, thanks to the integration of LED technology with advanced sensors and managements systems. This evolution is also the consequence of political/societal pressure to reduce energy consumption in the provision of light. However, Article 4 also highlighted that the *smart* light system is intertwined with the generation of new uses of light, and of new market players. Such evolution is expected to increase the importance of criteria other than energy efficiency in the evaluation of future lighting solutions. Article 4 concluded that the net contribution to energy saving of the future *smart* LED light will actually depend on how these different forces and drivers of change will interact. For this reason, Article 4 called for strong political guidance that goes beyond the support to development of new technologies.

The discussion part began by summing up, in the first two sections, the main conclusions of the four articles. It then proposed a new conceptualization of eco-innovation and confronted it with the one proposed by Pearson and Kemp. For the sake of simplicity, the two definitions have been labelled as *weak* and *strong* eco-innovation, to clearly mark the connections with the different positions in the sustainability debate. Indeed, in my view, the lack of connection between the sustainability and the eco-innovation literature has created a misunderstanding of the relations between innovation and sustainability. For this reason, some weak eco-innovations were incorrectly expected to increase the strong sustainability of the economic process. Whenever this did not happen, it generated the paradox discussed in the introduction. The discussion ended with some thoughts on the implications for policy makers, future research on eco-innovation, and the lighting case in the case of strong eco-innovation. In sum, the discussion emphasized the need for political guidance for eco-innovation, and a systemic integration of the rebound effect literature in future eco-innovation studies. In respect to the case study, the proposal highlighted some examples of innovations that could ensure the reduction of energy consumption for lighting by combining energy efficiency efforts with measures that reduce or control the final demand for lighting.

To conclude, fostering sustainability through technologies and innovations will require more policy and societal guidance, not less, because the innovative process generates profound changes in society. For this reason, innovation policy and energy (lighting) policy are two intertwined but separate areas, because it is not enough to solve relevant energy dynamics only through the use of innovation policy. In fact, energy policy has the duty to indicate the direction of future changes of the energy and lighting fields. I wish to close by suggesting that we, as a society, should carefully avoid any attempts to make dangerous short-cuts, based on faith about the ability to solve societal issues only through technology and innovation.

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